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Power Transformer Asset Management – Pracana Case Study

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Resumo

Os transformadores de potência constituem um grande investimento. Proprietários deste tipo de ativos têm a necessidade de estender a vida das suas frotas de transformadores.

Neste trabalho, é feita uma análise da gestão de ativos e de normas associadas.

Além disso, são analisados os transformadores de potência, os seus principais parâmetros, bem como técnicas e sistemas de monitorização existentess, com o intuito de avaliar a condição dos transformadores.

Uma análise comparativa é feita entre os modelos de cálculo do índice de saúde que permitem a avaliação da condição de um transformador de potência.

Nesta dissertação, é feita uma análise comparativa entre modelos de cálculo de índices de saúde que permitem a avaliação da condição de um transformador de potência.

Um índice de saúde é uma ferramenta que processa informação criando uma pontuação que descreve a condição de um ativo. Através deste índice é possível de forma objetiva determinar a condição de transformadores de potência, de forma a que sejam tomadas decisões de manutenção ou investimento.

Assim, é possível detetar possíveis ativos de risco evitando que estes falhem, permitindo um aumento do tempo de vida. O transformador que vai ser analisado era um transformador que se encontrava na subestação de Pracana. Devido a um rearranjo da rede no final de 2007, essa subestação tornou-se redundante. A subestação estava a alimentar uma rede de 60 kV através de um transformador de potência (150/63/10 kV) de 63 MVA, do tipo shell.

Este seria um caso único em Portugal, dado que normalmente os transformadores de potência só se encontram disponíveis para este tipo de avaliação, quando ocorre uma falha catastrófica, impedindo uma análise do envelhecimento, uma vez que as áreas de interesse encontram-se danificadas.

Dadas as razões que levaram à realização de um abate controlado neste transformador, foi possível a recolha de um conjunto de informações que permitiu a análise da condição, essencialmente, da degradação térmica dos materiais isolantes.

Utilizando os dados retirados durante o seu tempo de operação, bem como os dados recolhidos para a análise da degradação térmica dos materiais isolantes, é possível a aplicação de modelos de cálculo de índices de saúde.

Assim, foram utilizados métodos de avaliação da condição do transformador para que seja feita uma comparação entre eles e, se de facto o transformador ainda poderia estar em operação mais anos.

Estes modelos vão avaliar diferentes subsistemas do transformador culminando num resultado final que indicará a condição geral do transformador.

Abstract

Power transformers comprise a great investment. Owners of this type of asset have a growing demand to extend the life of their transformer fleets. In this work, an analysis of the asset management and associated norms is made.

In addition, power transformers are analysed and their key parameters as well as the existing monitoring techniques and systems in order to assess the condition of power transformers.

A comparative analysis is made between health index calculation models that allow the evaluation of the condition of a power transformer.

A health index is a tool that processes information by creating a score that describes the condition of an asset. Through this index it is possible to objectively determine the condition of power transformers in order to make maintenance or reinvestment decisions.

Thus, it is possible to detect possible risk assets preventing them from failing, allowing an increase in the life time.

The transformer to be analysed was a transformer that was in the substation of Pracana. Due to a network rearrangement at the end of 2007, this substation has become redundant. The substation was feeding a 60 kV network through a 63 MVA, shell type power transformer (150/63/10 kV).

This was considered a unique case in Portugal, since power transformers are only available for this type of assessment, when a catastrophic failure occurs, preventing an analysis of ageing, since the areas of interest are damaged.

Given the reasons that led to a controlled scrapping in this transformer, it was possible to collect a set of data that allowed the condition analysis, which focused mainly on the thermal degradation of insulation materials.

Using the data collected during its operating time, as well as the data collected for the analysis of the thermal degradation of insulation materials, it is possible to apply health index calculation models.

Methods of evaluating the condition of the transformer were used to make a comparison between them and if in fact the transformer could still be in operation for more years.

These models will evaluate different subsystems of the transformer culminating in a final result that will indicate the general condition of the transformer.

Acknowledgements

"If I have seen further, it is by standing on the shoulders of giants."

Isaac Newton

The above quote has two meanings that are important to me. First of all, I would like to thank the *giants* with whom I worked at Efacec.

For their unwavering support, motivation, and above all, for their knowledge that helped me complete this last stage as a college student. I would like to thank Professor Hélder Leite and Dr. Nuno Silva for being my mentors, for giving me this opportunity and having believed in my value since the beginning. To Dr. Hugo Campelo, for his accompaniment, for his patience and availability and that allowed that this work was a work of which I am proud.

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Miguel

"The greatest danger for most of us is not that our aim is too high and we miss it, but that it is too low and we reach it."

Michelangelo Buonarroti

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Abbreviations and Symbols

ABB	Asea Brown Boveri
BSI	British Standards Institution
CBM	Condition Based Maintenance
DGA	Dissolved Gas Analysis
DGAF	Dissolved Gas Analysis Factor
DSO	Distribution System Operator
EDP	Energias de Portugal, S.A.
ERDF	Électricité Réseau Distribution France
FAT	Factory Acceptance Tests
FRA	Frequency Response Analysis
HI	Health Index
HV	High Voltage
IAM	Institute of Asset Management
IEC	International Electrotechnical Commission
IED	Intelligent electronic device
IEEE	Institute of Electrical and Electronic Engineers
ISO	International Organization for Standardization
GE	General Electric Company
LF	Load Factor
LV	Low Voltage
MR	Maschinenfabrik Reinhausen
OEM	Original Equipment Manufacturer
OIP	Oil Impregnated Paper
OLTC	On-Load Tap Changer
OQF	Oil Quality Factor
PAS	Publicly Available Specification
PD	Partial Discharge
PM	Planned Maintenance
RBM	Risk Based Maintenance
RCA	Root Cause Analysis
RCM	Reliability Centered Maintenance
REN	Redes Energéticas Nacionais, SGPS, S.A.
TAI	Transformer Assessment Index
TBM	Time Based Maintenance
TICM	Transformer Intelligent Condition Monitoring
TSO	Transmission System Operator
TV	Tertiary Voltage
UHF	Ultra High Frequency
WO	Work Order

Chapter 1

Introduction

In this work, an analysis of the asset management and associated norms is made.

In addition, power transformers are analysed and their key parameters. Besides that, the existing monitoring techniques and systems in order to assess the condition of power transformers are analysed.

In the practical component of the dissertation, methodologies are applied for the calculation of health indexes in a power transformer that was subject to a controlled scrapping. After the application of these methodologies a comparative analysis between them is made in order to understand if, for example, these go against what was analysed.

This chapter presents the motivation and the achievable objectives of this work.

At the end of the chapter, the dissertation structure is briefly described and the dissemination of the results obtained with the work is presented.

1.1 Motivation and purpose

Power transformers are essential components since they are expensive equipment. Owners of this type of asset have a growing demand to extend the life of their transformer fleets by improving their financial and technical performance.

In order to have a balance between investment, maintenance costs and operational performance, there is a need for economic and financial reports to be provided to make asset decisions.

The use of health indexes has become a common method for conducting assessments on assets either individually or in large groups. The health index represents a practical tool that combines results from routine inspections, operational observations, laboratory and on-site testing, resulting in an objective and quantitative index, providing the overall health of the asset, usually in numerical form.

Through this methodology, the asset manager can detect and quantify long term degradation and degradation states that indicate the end of life approximation or high risk of asset failure. This allows the creation of efficient maintenance plans and replacement strategies based on the condition of assets. In addition, it allows the identification of which assets could benefit from life extension measures.

Thus, the health index provides a method that employs engineering knowledge and experience to predict future asset performance, probability of failure, and replacement plans.

However, it should be noted that this index is highly dependent on the data that is available for most assets (when the assessment is for a group of assets). This limitation will dictate which assets can be assessed. Therefore, for the evaluation of the condition of a transformer it is necessary that the method used is based on existing data.

1.2 Structure and Organisation

In this section it is intended to indicate the main phases of the work developed, as well as the structure adopted for the accomplishment of this dissertation. After the motivation for the development of this work, it will be presented in Chapter 2, the literature review on the current state of asset management presenting the definition of assets and asset management and the reason for its standardisation. In this chapter, different types of asset maintenance strategies are also presented.

In Chapter 3, the literature review on the power transformer is presented. In section 3.1, a description is made of the components that constitute a power transformer and the common faults associated with them.

In 3.2 an analysis of possible data that can be taken from an actual Factory Acceptance Test is made for future comparison with data of the transformer in operation allowing the investigation of discrepancies.

Through the analysis of 3.1 and 3.2, the key parameters that need to be monitored are identified and techniques that are used to monitor them are described (Section 3.3). Next, in 3.5, monitoring systems are analysed that result from the aggregation of parameters indicated in Section 3.3. Section 3.6 describes the literature review of transformer assessment indexes.

The description of the methodologies used and application in this work will be presented in Chapter 4. Throughout this chapter will be presented the tools used, data, methodologies of calculation and the final results obtained for each of the methodologies described in initial sections.

Chapter 5 contains the conclusions obtained in this work, describing the opportunities for improvement identified and conclusions of the analyses made. This chapter will also discuss the future steps to be taken in this work.

Chapter 2

Asset Management: overview

In this chapter the concepts of asset and asset management will be introduced and classified. Key points for the understanding of the work will be introduced. After that, it will be explained why it was necessary to standardise the asset management in order to create a line of sight between the business objectives and the way how a particular asset should be managed.

Then, a set of asset maintenance strategies are presented. These strategies are part of asset management as they have as their main objective the maximisation of the life cycle of the assets and the risks associated with them.

2.1 What is an asset?

An asset can be defined as a resource that performs a function or provides a service. For industries that rely on assets to achieve success, it is essential that their management is planned with a view to making them as profitable as possible. This involves defining a strategy for operating, preserving, improving and expanding assets throughout their lifetime.

The term "asset" is widely used nowadays, presenting different meanings depending on the area or sector concerned. At this moment, it is possible to identify five types of assets [1], these being:

- **Physical assets** — buildings, equipment, machinery, among others;
- **Human assets** — knowledge, skills, responsibilities, experience;
- **Financial assets** — profit, financial capital, shares, working capital, debts;
- **Intangible assets** — reputation, moral, social impact, image, external relations;
- **Information assets** — data in digital format, organisation and customer business information, financial performance information.

The life of an asset may not necessarily coincide with the period in which an organisation has responsibility for it. An asset can generate a real or potential value to a company over its useful life and the asset value for an organisation may change during its life.

According to [2] their value can be represented in a balance sheet of a company, can be listed in a repository of asset records, usually depreciates and deteriorates over time and its condition will benefit from good management.

In the case of physical assets, the process has several phases: the acquisition of the asset, its installation, operation, maintenance, refurbishment and retirement. It is also necessary to take into account customer satisfaction [3].

The following work will address the type of asset incorporated in the first point, physical assets, which include equipment, machinery, for example. This type of assets need to be holistically managed in order to achieve an organisational strategic plan [4].

Therefore, we can define an asset in two different ways: simple and complex. The difference between them comes from its dependence and interconnection with other assets of the organisation. For example, simple assets have no functional dependence on other assets. Complex assets or systems of assets depend on the operation of other equipment, eg the proper operation of a transformer depends on the correct operation of the windings, tap changer and insulating materials.

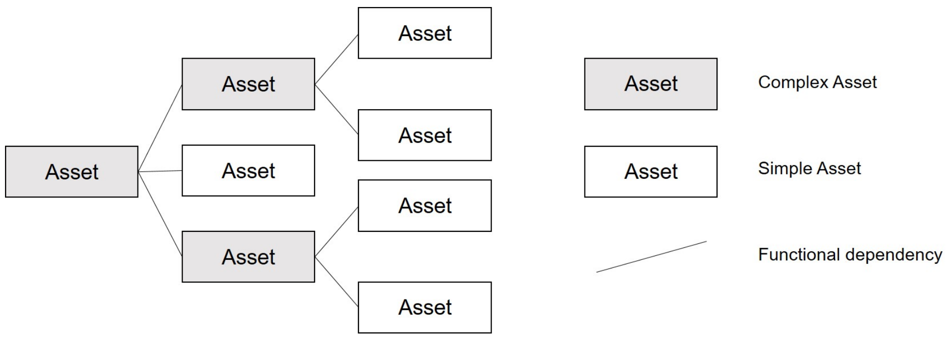

Figure 2.1: Connection between simple and complex assets [1].

2.2 Asset management standardisation

Nowadays, solutions must be based on relevant and up-to-date information about assets [3]. For an ideal management and with criteria it is necessary a detailed analysis of the assets. A large amount of data will need to be collected, processed, analysed and after that interpreted. Also, it will be necessary to identify the critical asset information. Asset management interacts with many functions within a company.

Assets can support more than one function and more than one functional unit within a company.

Basically, a few questions need to be answered before any decision is made. The questions are [3]:

- What data to collect?
- How to collect it?
- How to measure it?
- How to analyse it together with other data?
- How to optimise the results to achieve the best asset management practice?

Below are some examples of data that can be collected.

Table 2.1: Examples of asset information [3]

Type of information	Examples
Demographics	Location, type, voltage level, capacity, age
Condition	Inspections, tests, maintenance history, loading levels
Performance	Failure history, benchmarks
Functional	Capacity ratings, obsolescence issues, safety compliance
Criticality	Number of customers, priority customers, load, environment, safety
Costs	O&M, refurbishment, replacement costs

The interpretation of the data will lead to the adoption of management measures to answer different problems and opportunities that appear along the way. For management measures to be effective it is necessary to combine multiple types of information during the stages of collection, processing and analysis to create valid measures that will help the company decision making.

In this way, there are some ways to use them. One way is to use them regarding the history of the machine itself. This form turns out to be simple, because it makes a comparison term between the data being generated in reality versus the expected value in theory. If there is any discrepancy, it may be necessary to verify if the transformer is operating as it should.

Another way corresponds to a combination of several data available, for example, the attempt to find correlation between them versus the digital twin.

The last type would correspond to an aggregation of data, but using data from other physical assets too. This form would be the most refined form since it would not only use a combination of data. It would also check if there is an asset that stands out from the group in its operation or if there is some unit that does not behave as it should or even if like the previous proposal there is correlation between parameters, for example, a common cause for a non-standard discrepancy [5].

Maximising the return on investment in assets, while at the same time being operated in a safe and environmentally responsible manner, has become a concern of companies. While many companies can achieve these goals individually, often efforts to maintain up time, improve security, and ensure compliance are not aligned with each other. This non-compliance leads to wasted time, funds and resources for these parameters to be maintained individually [6].

By aligning these parameters in a common and comprehensive asset management system, specifications were created that allowed companies to create a line of sight between business objectives and how a given asset should be managed, create alignment and consistency throughout the organisation and incorporate the concept that a process is in place as in use and not just on paper.

2.2.1 Publicly Available Specification (PAS)

2.2.1.1 What is a PAS?

A PAS is a consultative document written and developed by a process based on the British standards model [7]. In this document the requirements and good practises of a specific theme are specified. This process can be initiated by any organisation or association and is subject to British Standards Institution (BSI) acceptance criteria.

The major difference between a standard English standard and a PAS is in consensus required for the approval of the document. While an English standard must gather total consensus of all stakeholders regarding the technical content present in the document, in the PAS the various stakeholders are invited to contribute, but their opinion may not necessarily be integrated. Thus, the time required to perform a PAS (generally 8 months) is considerably shorter when compared to the time required to prepare an English standard [7].

Those responsible for initiating the process have total control over the development of the content of the document. However, the BSI, through its procedures and its autonomy, assists in the process of consensus between the interested parties and in the design of the document, giving it credibility and ensuring technical robustness [7].

The content present in a PAS cannot disagree with any existing legislation applicable to the subject under analysis. PAS can thus be a step towards normalisation [1].

2.2.1.2 PAS 55

PAS 55 is a public available specification, published in 2004 by the British Standards Institution (BSI) in collaboration with the Institute of Asset Management (IAM). This specification provides guidelines and good practises for optimal management of the organisation's physical assets, so as to create a functional structure in the organisation that enables the continuous improvement of its asset management system [1].

The recommendations of this specification were made to address the industry's need to standardise asset management. These sectors have in common organisations with a high number of assets, and the efficient management of assets is a fundamental point in the growth and development of these organisations.

PAS 55 aims to increase efficiency in performance, risk and resources used throughout the life cycle of its assets. Asset management is based on the integration of the six key points as indicated in the Figure 2.2 [8].

The holistic and systemic view of the system is one of the focal points of PAS 55 because the analysis of the system is always carried out in a general scope of the processes of the organisation. The practises indicated in the standard always defend sustainable approaches in the management of physical assets [8].

Figure 2.2: Key principles and attributes of asset management [8].

PAS 55 is based on the plan-do-check-act methodology. This methodology proposes the need to carry out strategic planning (plan), execute and implement the projects (do), perform checks to detect anomalies or improvements in the project implementation (check), and finally some adjustments are made at discordant points verified previously (act) [8]. In this way, the projects or assets of the organisation are analysed continuously throughout their life cycle, trying not only to optimise all stages of these, but also throughout their life cycle within the organisation.

The PAS 55 specification is divided into two parts, PAS 55-1 and PAS 55-2. In the first part, the specifications and requirements to be optimised in the management of the organisation's physical assets throughout its life cycle [8] are indicated. The second part of PAS 55 makes the practical application of the theory stated in the first part of the norm.

2.2.2 ISO 55000

Given the popularity of PAS 55, and following discussion with organisations around the world, the specification was presented to the International Organisation for Standardisation as the basis for a new ISO standard for asset management. The proposal was approved resulting in the ISO 55000 family of standards, developed over the last years. On January 15th, 2014, the ISO 55000 series of standards was published.

The ISO 55000 series comprises three standards [9]:

- ISO 55000 provides an overview of the subject of asset management and the standard terms and definitions.
- ISO 55001 is the requirements specification for an integrated, effective management system for asset management.
- ISO 55002 provides guidance for the implementation of such a management system.

The content and structure of ISO 55001 is derived from PAS 55-1. Although similar, there are differences in requirements and some definitions.

Firstly, in the context of the organisation, the internal and external problems that are relevant to the organisation and which affect the organisation's ability to achieve the desired objectives in terms of the asset management system are identified. It is also ensured that asset management is aligned with the company's objectives and it is used the asset management decision making criteria when setting and updating asset management objectives [10].

In the monitoring, measurement, analysis and evaluation section, the evaluation and reporting areas are clarified in terms of asset management and performance as well as the effectiveness of the management system. A review of changes in the profile of risks and opportunities was included in the management review section [10].

In planning the objectives to be achieved, it is necessary to determine and document the decision-making method and criteria, the activities and resources to be prioritised, and the processes used to manage resources throughout their life cycles [10].

Although the focus of PASS 55 is physical assets, it also recognises impacts on other types of assets. ISO 55000 is also applied to physical assets, but its definition of assets extends to anything that has potential and value to a company. This value can be financial or non-financial depending on the company. Thus, for example, intellectual property can be managed in a manner that meets recognised asset management standards. This global definition leads to a simplification of terminologies and definitions.

The key focus areas of asset management that have been brought forward from PAS55 into ISO 55000 are [11]:

- Alignment of daily activities with organisational objectives
- Whole life cycle asset management

- Risk-based decision making, and the importance of leadership, consultation, competency development and information management.

2.2.3 Remarks

It was possible to conclude that the optimisation of asset management is critical to the performance of a company's business. The way you plan, operate, and maintain a set of assets is one of the key issues in increasing performance. In this way although PAS 55 was not an international standard, it was widely used by several sectors of industry until 2014.

The use of the Plan-Do-Check-Act methodology allowed organisations to implement a structure and develop processes for continuous improvement of their activities and procedures in order to face the external difficulties that companies face in their sector of activity.

For asset management to be standardised based on the practical methods of global asset management, ISO 55000 was created which provides a set of guidelines for continuous improvement in an asset management system.

The most significant change is related to the objective scope of application for standards. While PAS 55 is focused only on physical assets (with recognition of dependencies and applicability to other assets) ISO has been designed to be applied to any asset. Thus, the language used in ISO is more general and simple, to be interpreted within the different contexts of asset management [12].

When comparing PAS 55 with ISO 55000 it is found that the steps required for risk management are reduced. In terms of decision making, the requirements for planning optimisation are maintained, but described differently. Finally, the asset management policy has improved both the strategy and the objectives of asset management.

In conclusion, the fact that ISO 55000 is more generalised compared to PAS 55 allowed companies that were in PAS 55 to have no difficulties in obtaining ISO 55000 certification, since they would already fulfil most of the criteria [12].

2.3 Maintenance Strategies

One of the activities used to classify asset management of transformers is performing maintenance plans [13]. The main goal of maintenance is to maximise the life cycle of an asset and the risks associated with them, ensuring that it properly works under the best possible conditions and in the maximum amount of time possible.

However, for asset management to consider the objectives of the companies, it is necessary to have the balance between the benefits of a recommended maintenance measure for an asset and the costs of that measure must be considered.

The importance of maintenance comes from the need, giving the growing context of competition inside markets, of high production rates with 24/7 manufacture (ideally the machines would have to work all the time). This means that each setback, every shutdown, downtime, means loss of credibility, loss of customers because orders are not met in time.

The objective of having a maintenance strategy is to have solutions to prevent the occurrence of failures in the asset or to restore it. Maintenance strategies must be combined according to the objectives to be achieved:

- Reduce downtime;
- Reduce the number of faults;
- Increase safety;
- Improve equipment performance;
- Minimise costs and production losses;
- Improve the quality of production;
- Increase equipment life.

Maintenance strategies will be presented. These strategies can be divided into different approaches (Figure 2.3) which lead to different asset availability and maintenance costs.

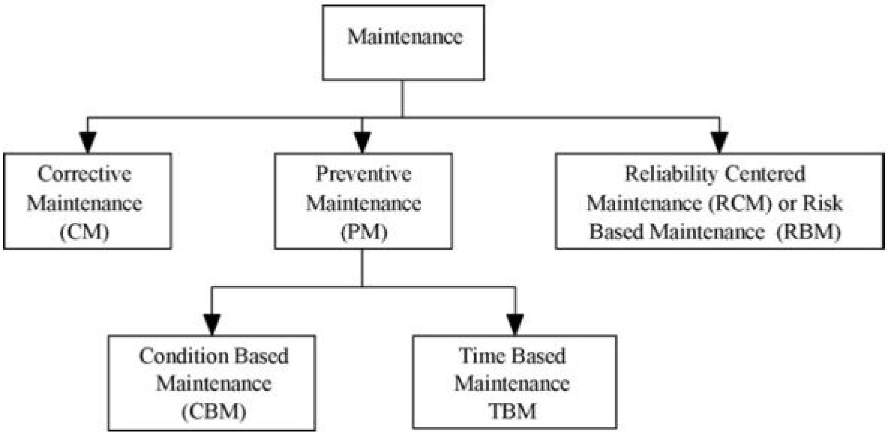

Figure 2.3: Classification of maintenance strategies [13].

2.3.1 Unplanned maintenance

Unplanned maintenance is usually put into practice when malfunctions appear suddenly and unpredictably. That is, it applies when an equipment stops working. This type of maintenance requires the placement of an immediate functioning equipment. Actions are performed only after encountering the problem and the goal is to the equipment to regain the necessary conditions to function as before the irregularity.

This type of maintenance is called reactive maintenance and allows you to save time since there is no need in creating a maintenance plan and nothing is done as long as everything is working as it should be. However, the great disadvantage of this strategy is that when a problem occurs in the asset, it suffers from considerable downtime when compared with other maintenance strategies [14].

2.3.2 Planned maintenance

In cases where this policy is adopted, maintenance is organised well in advance and the use of previously defined maintenance plans are put into practice at the most appropriate moment. In most cases, it is performed at regular time intervals, T [15]. This planning involves the preparation and programming of the planned maintenance (PM), however there is no standard procedure. It is based on the knowledge from technicians and engineers acquired over the years of work [16]. Other way PM is applied is through recommendations from the Original Equipment Manufacturer (OEM).

PM comprises two major types of maintenance: preventive and corrective maintenance. It is up to the staff to determine the appropriate method to apply in order to avoid potential failure or even collapse of the equipment.

2.3.2.1 Preventive maintenance

Preventive maintenance aims to prevent the failure from occurrence. Using this type of maintenance longer lifetime of the asset is possible and costs reduced, improving availability. This type of maintenance is required to prevent failures or even the total loss of the asset. They are based on facts that were acquired through the processing and analysis of data collected from the equipment [16].

The disadvantage of this strategy is the need to consider the most pessimistic scenario when a maintenance plan for the equipment is being developed in order to completely avoid any type of shutdown [14].

In this way, maintenance is going to be done more often than would be necessary resulting in high costs for companies.

It is possible to define two types of preventive maintenance techniques and both work towards better maintenance decision making:

- Time Based Maintenance
- Condition Based Maintenance

Time Based Maintenance

TBM consists in performing periodic maintenance interventions according to a time schedule on the equipment. Essentially, TBM assumes that the failure behaviour of the equipment is foreseeable however this method might become expensive if the inspection intervals are short due to unnecessary checkups, shutdowns and the need of specialised staff to undergo the maintenance [17]. Yet it can detect at early stages faults in equipment which can produce long term savings to the company.

The figure 2.4 represents how this method assumes the failure rate trends.

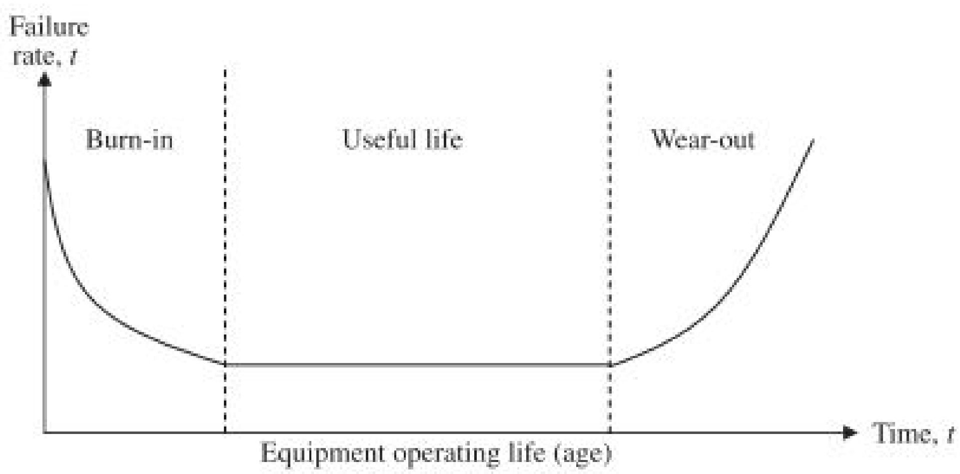

Figure 2.4: Bathtub curve [18].

This type of failure rates can be divided in burn-in, useful life and wear-out [16]. The burn-in phase corresponds to the phase where the equipment experiences a decreasing in failure rates in his life cycle. After that the equipment enters a near constant failure rate called useful life period which occupies most the operating life.

Finally, the equipment enters the wear-out phase where the equipment starts to experience increasing failure rates [16].

Condition Based Maintenance

Predictive maintenance

The current development line states that there is a need to know the current condition of the equipment in order to find a strategy that optimises, for example, the life cycle of the asset. So, it is based on the concept of condition monitoring.

This type of maintenance leads to a periodic or continuous control of the assets, based on the analysis of the information collected through its monitoring.

Based on the crossing of a set of data collected during the operation of the equipment it is possible to make an evaluation of the technical condition of the machine and to predict the ideal moment to carry out interventions leading to a minimisation of the associated costs. In other words, through this type of monitoring it is possible to find trends and failures which will allow the company to anticipate in a timely manner [16].

This collected information used for forecasting future problems may come from statistical machine data or a more comprehensive form of statistical data from all existing machines of that type.

There are a number of aspects that need to be taken into account when discussing this type of strategy[14]:

- **Identification of indicators** — In an initial phase, there is the need to identify the physical parameters to be measured. The parameters must be reliable and capable of detecting what is going to be determined, that is, the wear and ageing that the machine suffers during its operation. The choice of indicators with the characteristics described above will allow the prediction of future failures, but these predictions will only be relevant if the indicators are directly related to the physical state of the asset. In this way, there will be a need to know in depth the machine that will be monitored.

- **Measurement of indicators** — As the name implies, this topic portrays the component of measurement methodologies. The challenge in this component is how the measurements should be made in a real system, eg a power transformer in operation. It is also necessary to think about the type of equipment that is intended to be used in the monitoring, which may vary depending on the objectives.

- **Modelling of indicators** — Another key point corresponds to the modelling of the physical indicators previously chosen. When modelling the indicators, it will then be possible to detect discrepancies and start the predictive component. To be able to provide good predictions, there is the need to choose suitable models and choose a reliable parametrisation. In this way, the possibility of being able to integrate several models would allow to gain advantages, for example, in the verification of the data that was collected, processed and analysed.

- **Forecasting of indicators** — With the help of forecasting techniques it is possible to create a model that allows an indicator to obtain an estimate of its future values. This indicator or indicators have already been chosen and their way of being measured in advance by the points previously explained.

  This type of forecasting is done through techniques associated with statistics and evolutionary computation.

- **Decision Making** — After detecting a future fault in the equipment there is the need to respond to this new problem that has arisen [16]. In this way, in addition to trying to solve this problem (discovering the origin of the fault), it is essential to choose the right moment to do so that continuity of service is minimised. Thus, the ideal situation would be a platform that would not only allow detection but would also help decision-makers.

2.3.3 Corrective maintenance

This type of maintenance activity is performed upon the occurrence of failure and it is the most basic type of maintenance (also called run-to-failure or reactive maintenance). When the asset fails, it can cause service interruptions (high equipment downtime) and affect the system performance, and it is necessary to repair the asset so that it can fulfil its function again. In other words, the component is operated until it fails [19].

It is difficult to have an idea of the associated budget due to the unpredictability of failures and possible repair costs. Moreover, only intervening when a failure occurs is incurring the risks associated with the failure, such as collateral damage to other assets. This type of maintenance is recommended for assets with non-critical function or do not bring great added value to the productive process and that are easily replaced or repaired.

The difference to unplanned maintenance is that in case is necessary to replace components, they may already be in storage and prepared to be used immediately as needed. So, the failure is only treated as it appears, however the means to deal with it are already defined and prepared.

Some examples of this type of maintenance carried out by Efacec in transformers are given in Annex A.1.

2.3.4 Reliability Centered Maintenance

Initially the methodology Reliability Centered Maintenance (RCM) developed initially by the aeronautical industry [13]. Since then, the RCM has been used more comprehensively and its fundamental purpose is to preserve the function or operation of the system at a reasonable cost.

The general meaning of the RCM maintenance is in optimising the maintenance plan based on risk analysis [20].

RCM combines a set of maintenance techniques (proactive and reactive) in order to reduce the system risk [1]. Proactive maintenance techniques are performed prior to the occurrence of the fault to prevent their occurrence or at least reduce their likelihood. Reactive maintenance techniques are performed after the fault occurs [21].

This methodology is a continuous process, and the results of reliability and cost of maintenance are constantly analysed. In addition, it aims to achieve high levels of safety of people and goods directly related to the asset and an adequate availability of the asset for production.

RCM allows not only prioritising effective maintenance actions, but also to determine action plans in which issues related to replacement and remodelling are made, for example, if it is economically preferable for a transformer to undergo maintenance actions or to be replaced [19].

The application of this methodology implies that 7 basic questions [22]:

1. What are the functions and performance standards of the item in its current operational context? - **Identification of functions**
2. In what way, does it fail to fulfil its functions? - **Identification of functional failures**
3. What causes each functional failure? - **Fail mode**
4. What happens when each failure occurs? - **Effect of failure**
5. In what way does each failure matter? - **Consequences of failures**
6. What can be done to predict or prevent each failure? - **Maintenance tasks**
7. What should be done if a suitable proactive task cannot be found?

By answering the first five questions it is possible to obtain detailed information about the transformer in its operation context and to identify the main causes of failures. The last two questions identify the maintenance procedure for each failure mode of the transformer [22]. The advantages of RCM are [23]:

- Guarantees low possibility of occurrence of high- risk failures
- Saves money paid for unnecessary close timed inspections in case of TBM
- It reduces the unnecessary shutdowns for low risk failures.

Its disadvantages are [23]:

- Being less understood by maintenance engineers and technicians;
- Needing for a large amount of data about failure rates, modes.

2.3.5 Root Cause Analysis

This methodology aims to identify the events that led to the occurrence of a fault in an equipment. After the fault occurrence, this method analyses, in a structured way, the events that are likely to have caused the fault. Thus, it identifies the true causes of the malfunction, so that it does not occur again. Detailed knowledge of a given failure allows corrective actions to be taken [22].

The RCA method involves answering to three questions when a malfunction occurs:

1. What was the fault?
2. What were the causes of the breakdown?
3. What actions must be taken so that the malfunction does not occur again?

2.3.6 Remarks

The implementation of maintenance plans is one of the main activities in asset management such as transformers. Ageing of a transformer can be accelerated if maintenance is not done within the indicated period and if fault identification is not made in a timely manner.

This section described the maintenance strategies. In the last decades, strategies have emerged that seek to integrate the various existing maintenance strategies, exploring the advantages of each one. Examples are CBM, RCM. These strategies need information of the asset in its operational context and seek to know the type of failures, their effects and the consequences that arise from the occurrence of a failure.

The development of a maintenance policy is necessary and should be adapted to each asset, considering the risks assumed by the consequences of its failures, maintenance costs and reliability indicators.

2.4 Portuguese Distribution System Operator example

The Portuguese Distribution System Operator (EDP Distribuição, SA) defines asset as "Set of goods and rights necessary for a maintenance, support of activities and consequently of the business, being able to identify itself, by its materiality, and by the time in which they remain in the possession of an organisation" [24].

As you can see, the definition of asset according to the DSO is generalised, which includes assets that won't be analysed in this work. According to [24], the amount of distribution network assets at the end of the year, broken down by their main types, are shown in the figure 2.2:

RUBRICA	UNID	31/DEZ/14	31/DEZ/15
Subestações			
Unidades	nº	416	419
Transformadores	nº	725	731
Potência instalada	MVA	17 401	17 608
Linhas (inclui ramais)	km	**81 694**	**82 175**
Aéreas	km	67 028	67 336
AT (60/132 kV)	km	8 844	8 904
MT (6/10/15/30 kV)	km	58 184	58 433
Cabos Subterrâneos	km	14 666	14 839
AT (60/132 kV)	km	531	523
MT (6/10/15/30 kV)	km	14 135	14 316
Postos de Transformação			
Unidades	nº	66 719	67 063
Potência instalada	MVA	19 969	19 993
Redes BT (km)		**141 829**	**142 325**
Aéreas	km	108 586	108 936
Subterrâneas	km	33 243	33 389

Table 2.2: Installations and equipment in service [24]

Currently, EDP Distribuição, SA has made a gradual commitment to the technical monitoring of its assets, their identification and the evaluation of the risks associated with them. In this way, it is possible that the performance is done at the right time, before the failures occur, allowing a good performance of its technical assets with justified costs and controlled risk. In addition, it is also possible to define and sustain rehabilitation plans for prioritised assets based on the level of risk.

In parallel, focus has been placed on the R&D department (as it has been transversal in many companies) so that new methodologies, techniques, solutions can emerge and that their eventual incorporation translate into advantages such as reduction of maintenance costs and improved performance of assets.

So the effort has been on on-line asset tracking methods. Through the integration of mechanisms that allow this type of monitoring (sensors, for example) the path will be a predictive maintenance allowing a more in-depth analysis of the behaviour of the assets and it is possible to determine the best timing for the occurrence of maintenance. This way, unnecessary service interruptions are avoided and the occurrence of failures is anticipated, still acting at an early stage of the problem [25].

2.5 Portuguese Transmission System Operator example

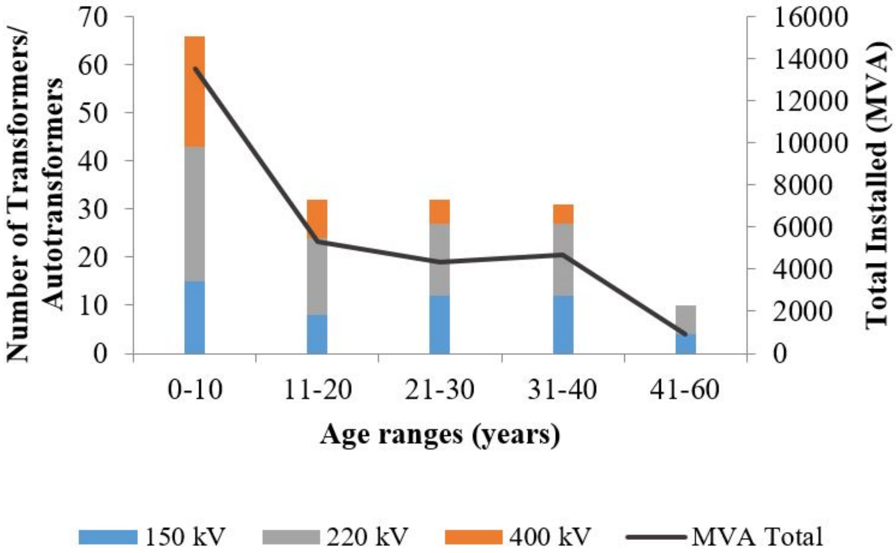

Figure 2.5: Age distribution of the transformers and autotransformers of the Portuguese National Electricity Transmission Grid (RNT) [20].

The operator of the National Transmission Network in Portugal (RNT) is Redes Energéticas Nacionais, S.A (REN). In 2009, it had about 170 transformers of great power and autotransformers in the networks of 150, 220 and 400 kV. In that year and in previous years, a network reinforcement and expansion program was initiated, which led to an increase in the number of assets, namely installed units and number of substations. Figure 2.5 shows that most of the assets are in the range of 0 to 10 years which comes from the programs mentioned above.

The 0 to 10 year group accounted for 47% of total installed power and most transformers had a rated power of 120 MVA or higher. Only 3% of the transformers were older than 41 years. These older units still had power ratings of 60 to 90 MVA.

This program led REN to strategically consider the relocation of several power transformers. Power transformers that had been in service for some years need some refurbishment in order to increase their lifetime. This life extension is defined according to an assessment of the condition of the transformer that allows the evaluation of life expectancy and the cost-benefit analysis of both the refurbishment and relocation of the transformers.

Chapter 3

Asset management: Power Transformers

Power transformers represent high value physical assets. In addition to its value, its function is indispensable and safety measures are necessary due to the high danger in case of failure, for that reasons they require close attention from companies. It is vital to determine its condition to prevent it from failing and impact the availability statistics, reliability and the companies' credibility. Besides that, if the transformer fails it will contribute to economic losses to the company due to the possible transformer replacement costs and environmental damages [5].

Correct planning of maintenance interventions can increase the life of a transformer and maximise it.

The life time and the degradation of a transformer are mainly affected by the following properties [26]:

- **Dielectric**, the insulation of the transformer, for example in the windings;
- **Magnetic**, the condition of the core and the structure that surrounds it;
- **Switch**, a mechanism that allows the voltage regulation of the transformer;
- **Mechanical integrity**, the degradation that the various components of the transformer undergo in operating conditions, such as the tank, the cooling system, etc.

This chapter will describe the transformer constitution, the parameters that will be evaluated throughout the work, and will be considered the most critical since an unusual change in them, both individually and collectively, can have disastrous consequences for both the transformer and the organisation that owns the power transformer.

A factory assessment test of a transformer will be presented and indicated which information would be collected and be used as reference in future monitoring.

In addition, it will be explained which phenomena arise from the variation of the so-called critical parameters of a power transformer, the different condition monitoring techniques and systems.

3.1 Transformer constitution

According to [27] the main functional subsystems of the transformer are the following:

- Active part (magnetic core and windings)
- Bushings
- OLTC
- Cooling System
- Oil containment and preservation (tank)

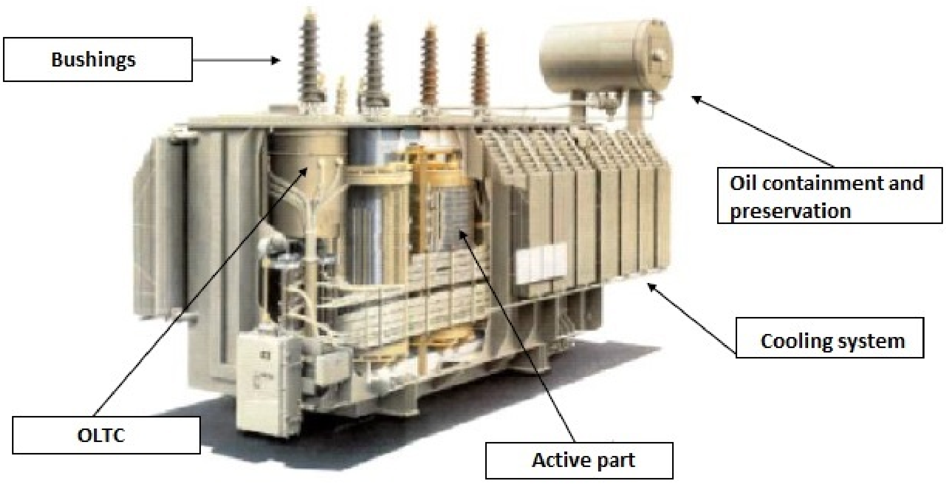

Figure 3.1: Transformer Functional Main Subsystems [27].

3.1.1 Magnetic Core

The main function of the magnetic core of the transformer is to provide a path for the magnetic flux to flow from one winding to the other with the least possible losses. For its function to be possible the magnetic circuit must have a low magnetic reluctance to conduct the magnetic flux and a high electrical resistance to reduce the losses by eddy currents also known as Foucault currents (loops of electrical current induced within conductors by a changing magnetic field in the conductor). Eddy currents cause heating and energy losses within the core decreasing the transformers efficiency.

One way to reduce these unwanted losses is to build the transformer core from thin steel laminations. These steel transformer laminations vary in thickness (0,2mm-0,3mm) and are electrically insulated from each other by a thin coating of insulating varnish or using an oxide layer on the surface. There are several technologies to increase the magnetic permeability. Some focus on the different chemical compounds other in how the steel is rolled and how the laminations are joined together in the core joints [28].

The laminations can be ferromagnetic or made of amorphous materials. The laminations of the transformer during its lifetime can suffer mechanical stress due to the high winding currents. This mechanical stress can lead to small inaccuracies and if there are gaps between the joints, there may be partial discharge activity and circulating currents [28].

Due to transportation or constructional mistakes, the lamination of the magnetic circuit may suffer damage between the insulation layer and the laminations. These damages could lead to short circuits which leads to circulating currents and the generation of heat. This generation of heat will lead to the degradation of the insulation layer which will produce damage not only on the insulation paper as well as the core itself [28]. Another reason for overheating is related to grounding of the core. This will allow the existence of circulating currents that will generate heat leading to local overheating. If the grounding of the core is lost there will be partial discharges that can be detected through DGA (see section 2), which will be explained later in this chapter.

3.1.2 Windings

Windings are one of the most important part of the transformer since they are the main current-carrying conductors wound around the laminated sections of the core. They constitute the electrical circuit of the transformer and according to the relative arrangement between the high and low voltage windings, the coils may be concentric or alternating. The primary winding is given to the winding through which the feed is made and secondary to the other [29].

They can be made of copper or aluminium and can be in wire, bar or band. They are commonly made of copper conductors which are electrically insulated electrically from one another to prevent eddy currents. Like the core of the transformer, they are covered by a layer of varnish and then spun with paper for insulation.

Problems in windings are considered the most critical that a transformer can experience. Faults of this type cause the transformer to not perform its functions. Repairing the windings is costly, time-consuming and requires that the transformer be out of service for a long time [28]. If there are no maintenance plans, backup transformers, such a failure can have disastrous consequences resulting in direct and indirect costs for the industrial, commercial and residential sectors as well as having negative impacts on the social life of electricity users [17]. Thus, sometimes it is preferable to replace the transformer instead of repairing it.

Considering the position of the core and the windings, the transformers can be of the type Shell or Core.

Windings can be deformed by electromechanical forces produced by large currents resulting from earth faults or switching operations or by electrical breakdown.

The impacts of these forces depend on the design of the transformer and the location of the incident. Expansion forces lead to conductor or insulation tearing. Without adequate mechanical support and withstand strength, the windings can suffer buckling. The deformation of the windings can result in short circuits between layers, phases, phase-to-earth [28].

Electrical disruption of the insulation is a condition that can worsen over time and in this way can be considered as a failure mode but also as an aging mechanism.

The severity of the electrical breakdown can range from relatively harmless PDs to a complete breakdown with severe consequences. PDs damage the solid insulation leading to the reduction of insulating properties. They can develop to even more serious failures with higher discharge energy [28].

Windings in large power transformers consist of paper wrapped insulation on the windings [30]. This paper contributes to dielectric and mechanical strength. Through mechanic withstand the windings are kept in the same place even suffering mechanical stresses.

The paper contains 90% cellulose [30, 31] and the factors or mechanisms that contribute to its degradation include thermolysis, hydrolysis and cellulose reaction. The cellulose degrades slowly as the polymer chain breaks down during the operation, releasing compounds into the oil. The degradation of the paper to a certain extent leads to the loss of mechanical resistance that endangers the electrical integrity of the transformer. Damaged paper cannot provide adequate physical support for windings and this can lead to premature failure [31].

Through the degree of polymerization (DP), it is possible to deduce the health of the paper [23, 30, 31, 32]. Glucose monomer molecules are bonded together with glycoside bonds to form cellulose. The average length of the cellulose polymer, measured as the average number of glucose monomers in the polymer chins, is referred to as DP [33].

However, to obtain a sample of paper it is necessary to open the transformer tank and, furthermore, there is no guarantee that the location from which the paper winding was taken is representative [30]. As it is necessary to open the transformer other prognostic models are used.

3.1.2.1 Chendong model

Furans are generated due to cellulose paper ageing and are found in the oil of transformers in operation [34, 35]. This analysis is used instead of the direct measurement on insulation paper, because it is a non-intrusive analysis. This measurement is used as bulk measurement of DP of insulation paper [30].

One of the models developed based on the observed relationship between the DP value and the 2FAL concentration is the Chendong model. The Chendong model estimates the DP of the transformer winding insulation based on the concentration level of 2-Furaldehyde (2FAL) [17]. 2FAL is the most predominant compound generated by cellulose paper ageing [36].

Equation 3.1 is a linear regression based on data collected on transformers using Kraft insulation paper and free-breathing conservator [34]:

$$log(2FAL) = 1.51 - 0.0035DP \tag{3.1}$$

As can be seen, there is a relationship between the concentration level of the logarithm of 2FAL and DP. Equation 3.1 is applied to approximate the average DP and estimate the ageing for the insulation of the transformer winding.

Given the estimation of DP from the equation 3.1, equation 3.2 is used for the calculation of the elapsed insulation life of a transformer:

$$Elapsedlife(years) = 20.5 \times \frac{DP_t}{DP_0} \tag{3.2}$$

Where DP_0 is the DP of a new transformer and DP_t the DP of a transformer at time t. The value 20.5 corresponds to the minimum normal insulation life expectancy of 180.000 hours ($\sim$ 20.55 years) [37].

3.1.2.2 Temperature based model

The degradation of the paper corresponds to a relation of DP, time, temperature and can be described mathematically as a first order reaction, using the Arrhenius law [20, 38, 39]:

$$\frac{1}{DP_t} - \frac{1}{DP_0} = A \times exp\left(-\frac{E_a}{R(T+273.15)}\right) \times t \tag{3.3}$$

- DP_t: degree of polymerisation after t hours
- DP_0: initial degree of polymerisation
- t: time in hours
- A: frequency factor (assumed as constant)
- E_a: activation energy (J$\cdot$mol^{-1})
- R: ideal gas constant (8.314J^{-1}.K^{-1})
- T: temperature (°C)

Although ageing or deterioration of insulation is a time function of temperature, moisture content, oxygen and acid content, according to [40] insulation temperature will be the only parameter.

Temperature at which degradation occurs is essential to know the current state of the solid insulation. Temperature can be measured through fiber optics; however, this equipment must be installed during construction [40]. For older transformers, the temperature in the winding is measured through from the top oil or estimated from the load.

Since the temperature distribution inside the transformer is not uniform, some areas of the transformer are at higher temperatures than others. These areas are called hot spots. At these points, it is expected that the insulation will degrade faster and will represent the weakened part of the solid insulation [40]. The estimates of the isolation condition through equation3.3 evaluate the insulation of the hot spot.

3.1.3 Bushings

Bushings main function is to take the current of the external electrical grid to the active part of the transformer. This current will pass through the main tank and so it is important that the bushings allow this without the mechanical component of the tank being compromised. The majority of bushings are as old as the transformer, being at the threshold of its useful life (25 years).

Its main components are the main bushing conductor (lead), porcelain/polymer insulator, test derivation, paper core insulation of condenser bushings (condenser core), insulating oil, resin insulation, SF6 insulation, capacitive tap and conductor [27].

Bushings are easy to replace and compared to other transformer components are cheap. A failure in this component may lead to damage to other components with more important functions and which are more expensive.

Therefore, knowledge of the current state and regular monitoring becomes essential. In terms of functional failure modes, an example would be the excess in leakage current between the inner conductor of the bushing and casing [27].

Bushings are exposed to many of the failures that occur both in windings and in the insulation system. For Oil Impregnated Paper (OIP) type bushings, degradation may happen due to high temperatures and moisture. Insulation can also be damaged by high activity of PDs that result from high levels of moisture [41].

A failure in the bushings due to excessive moisture of the insulation, lack of insulating oil in critical areas or leads to a reduction of the capacitor's dielectric capacity, causing an explosion of the bushing.

Some preventive actions pass through the exterior visual inspection for the detection of cracks and oil leaks and control of the oil level and realisation of thermographies.

Regarding the periodicity of the control, most manufacturers consider that the bushings do not require maintenance, but advise periodic inspections and tests depending on the age and whether or not there is a history of anomalies.

3.1.4 Tap Changer

Tap changers are used to adjust the voltage on the secondary side of the transformer and are also considered critical components of the transformer. This adjustment is necessary to compensate for voltage variations or to provide flexibility to a system voltage [28]. Tap changers are used in industry and transmission as they depend on the control of the transformer output voltage.

With the expansion of power systems, it is necessary to change the transformer taps several times during the day in order to obtain the proper voltage in the system according to the load demand. Since there is no possibility to disconnect the transformer from the system to perform offload tap changing most of the power transformers, nowadays, have on-load tap changers (OLTC).

Since OLTCs are operated automatically and are frequently operated, the mechanical wear of the switching mechanisms is the main source of failures. are, together with fans and electric pumps, the only components of the transformer that have particular wear because they are not static. Therefore OLTCs need special maintenance actions.

An interruption of current in an OLTC leads to arcing, which will consequently lead to the production of gases. These gases are the same created by dielectric failures inside the main tank which can lead to false interpretations [28].

Examples of faults in OLTCs are given in Annex A.2.

3.1.5 Oil

Mineral oil is widely used in transformers. The reasons are not only due to its insulating properties but also by the fact it functions as a cooling agent. The oil flows through the active part of the transformer and "drags" the heat resulting from the operation of the transformer.

In addition, the physico-chemical constituents of the oil provide pertinent information regarding the condition of the transformer. By means of a monitoring technique that will be elaborated in section 3.3.1 it is possible to detect possible failure modes. The quality of monitoring and maintenance of the oil is essential to ensure the proper functioning of the power transformers.

New oil Characteristics:

- High breakdown voltage to guarantee the dielectric demands imposed by the operation of the transformer
- Low viscosity to ensure good heat transfer from the inside of the transformer to the outside
- Resistance to oxidation (ageing) to ensure a longer oil life

3.1.5.1 Oil parameters

Breakdown Voltage

Indicates the presence of contaminants such as water or particles in the oil. However, a high value of this parameter may not mean total absence of contamination. On the other hand, a value below the limits may not guarantee the insulation and cause a defect.

However, for monitoring the transformer, the isolated analysis of this parameter is not determinant, since the action of moisture in conjunction with oxygen and temperature will destroy the solid insulation well before the appearance of an abnormal value of the breakdown voltage.

Colour and Aspect

Basic test that gives us an expedited indication of the state of oil degradation.

The colour of the oil varies from almost transparent to yellow, orange, brown and black. Condition varies from new oil to extremely bad/deteriorated or contaminated oil (Figure 3.2). The presence of certain components such as fibbers, cellulose, dirt usually give the oil a turbid appearance [42].

Figure 3.2: Variations in insulating oil colour, for different oil conditions [42].

Water Content

A low water content in mineral insulating oils is required to maximise the life of the solid insulation, to minimise metal corrosion as well as to achieve adequate breakdown voltage and low dielectric losses. Moisture has an impact on the reliability and life of the transformers.

A relation exists between moisture in oil and moisture in paper. Moisture migrates between the solid insulation and liquid insulation.

Solid insulation of the transformer is highly hygroscopic which leads to most of the water being in the paper. At high temperatures, water tends to move from paper to oil. In this way, it is necessary to know the oil temperature when a sample is taken in order to have a valid estimate of the water content present in the paper [42]. The relation between the water present in the oil and the paper and temperature is present in figure 3.3.

The solubility of the water in the oils depends on the state of ageing of the oils, the temperature of the oil and the type of oil.

Too high water content in the transformer is, in addition to increasing the ageing rate of the insulation system, potentially harmful due to the substantial risk of flashover between windings.

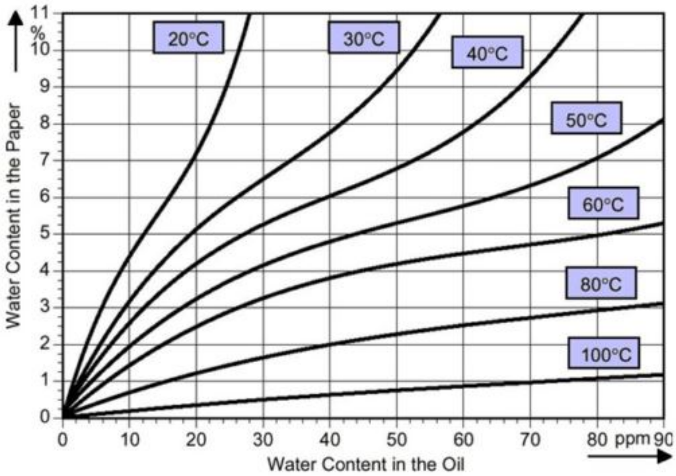

Figure 3.3: Equilibrium curve showing relationship between moisture content in oil and paper at different temperatures [42].

Interfacial Voltage

The interfacial voltage between the oil and the water provides a mean of detecting the presence of soluble polar contaminants and degradation products from the oxidation processes of the solid and oil insulators.

The higher the contamination, the lower the interfacial voltage of the oil. This characteristic changes very rapidly during the early stages of oil ageing. Oils with low interfacial voltage may not necessarily indicate a problem in the transformer, but a threat to the normal operation of the transformer in the future.

Acidity

The acidity of the oil is caused by the formation of acid oxidation products during the ageing process.

The dielectric strength and other properties of the oil are affected by the joint action of acids and other oxidation products, moisture and solid contaminants.

Acidity is minimal in a new oil. With the operation and natural ageing of the transformers, the oxidation of the solid insulation and oil provoke the increase of acidity in the oil. Acids attack solid insulators and accelerate their degradation.

Oils with high acidity may not indicate a transformer problem, but a future threat to normal operation.

There is a relation between acidity and interfacial voltage. As the acidity increases, the interfacial voltage decreases.

Viscosity

When the transformer is purchased the oil has low viscosity. However, as it is used the viscosity increases which causes its cooling function to entrain the heat from the losses, is not achieved so effectively.

Dielectric Dissipation Factor

This parameter indicates the level of dielectric losses (leakage currents) in oil when subjected to an alternating electric field. Indicates the presence of soluble contaminants in the insulating oil.

- Low values (<0.10 to 90 °C) of power factor in waste oils indicate low dielectric losses
- High values (between 0.10 and 0.50 to 90 °C) of power factor indicate a high oil deterioration
- Very high values (> 0.50 to 90 °C) of power factor indicate strong oil contamination

If the values reach the limits, the oil no longer performs the dielectric function and may cause a transformer failure.

Flash Point

The flash point is related to the temperature of the oil. Essentially, this point indicates the temperature at which the oil will ignite. When this value is exceeded (150 °C) the fire goes from an unsustainable situation (there is flame, but it is immediately extinguished) to self-sustaining (causing a fire), from there we are before the fire point. When the oil reaches a certain level of degradation, the operating safety margins are reduced and may lead to failure modes. However, by monitoring it is possible to detect this degradation in a timely manner and to carry out a treatment. This treatment will reset an established dissolved gas analysis trend.

3.1.5.2 Ageing of oil

The ageing of oil leads to a reduction of its hold fastness increasing the probability of the incidence of short circuits. Reduction of hold fastness may be due to contamination, increased water content or formation of gas bubbles [28]. The viscosity of the oil also increases, causing the cooling function to be reduced.

As noted above, gases are formed by overheating or discharges inside the transformer. The heating of the oil leads to the formation of hydrocarbons, whereas electrical failure produces hydrogen and acetylene. The degradation of the cellulose is associated with oxygen carbon dioxide and carbon monoxide [41].

There are some methods that allow to determine the cause for the formation of certain gases, however there is still no method to determine the location of the fault.

A recent problem concerns the presence of potentially corrosive sulphur compounds. If present in insulating oils, copper sulphide can be formed under certain conditions of operation.

3.1.5.3 Oil regeneration

The growth of environmental concerns has led to the development of methods for the treatment of degraded insulating oil, with the goal of restoring the properties suitable for reuse, so that there is a reduction of the waste oil to be disposed of.

This regeneration is done through natural clays based on magnesium and aluminium silicate and leads to the renovation of the properties of the oils that are in an initial state of degradation to values close to the new oil.

Despite these characteristics are similar to new oil, it is necessary to add an oxidation inhibitor to prevent the rapid ageing of the regenerated oil, when put to perform the same function as it performed prior to degradation.

3.1.6 Cooling System

Since an electric machine warms up during its operation, it is necessary to equip the transformer with an appropriate cooling system, to avoid reaching temperatures that may affect the insulation of the windings. Thus, a cooling medium is used, the oil, which has a duality of functions, ensures the cooling and the insulation of the transformer. The existence of this system is essential because the lifetime of the transformer is directly linked to the temperature at which the windings are exposed.

The cooling system collects the hot oil at the top of the tank and returns cooled oil to the bottom. The arrangement in terms of the cooling circuit can be seen as two oil circuits (exterior and interior) with indirect interaction. In the interior circuit the oil is used as a cooling medium and can flow either naturally or forced. Similarly, the outer circuit corresponding to the external cooling system (can also flow either naturally or forced) the most commonly used cooling medium is air. Ambient temperature helps cooling the transformer [41].

In order to designate the different the different types of cooling regime, different designations are used. The first and third letters refer to the nature of the refrigerant medium and the second and fourth letters to the nature of the circulation. The examples described in Table 3.1 correspond to the designations used by the IEC:

Table 3.1: Common cooling regimes used on power transformers [41]

Abbreviation	Internal cooling system	External cooling system
ONAN	Oil, natural	Air, natural
ONAF	Oil, natural	Air, forced
OFAF	Oil, forced	Air, forced
OFAN	Oil, natural	Air, natural
OFWF	Oil, forced	Water, forced

Pumps such as fans can suffer breakdowns. So, it is necessary that an exchange can be possible without being necessary to shut down the transformer. Thus, all cooling circuits must be provided with valves necessary to close each separate oil circuit [41].

3.1.7 Tank

The transformer tank has the function of protecting the active part (winding and transformer insulation system) from external factors such as mechanical damage and moisture penetration.

Regarding its mechanical part it has to store, contain, barring the total volume of oil inside the tank, radiator, expansion tank at an appropriate level, without leaks in valves, welds, gaskets, flanges, fittings, tubing, gaskets, or oil pumps [27].

In relation to moisture penetration, it must control the penetration of water and oxygen from ambient into the tank, radiator, expansion tank through gaskets, membranes, bag, keeping levels consistent with design.

The main problems may arise from damage to the outer coating and the ageing of joints and seals. Joints and seals have the function of keeping the oil inside and prevent the entrance of moisture from the outside. Over time the functions of both are not completely fulfilled with the possibility of oil leaks and moisture entering the main part. Thus, it is necessary to replace these components prior to the degradation explained above. In the case of coating, if it is damaged, corrosion of the tank will occur and over time the occurrence of leaks [28, 41].

3.2 Factory Acceptance Tests

Factory Acceptance Tests (FAT) are performed to ensure that the transformer has been assembled properly and will perform the functions for which it was designated ensuring safe operation. FAT consists of routine and/or design, and other tests as applicable in compliance with specified international standards as well as other specific tests that may be requested by clients.

FATs should provide reference data for subsequent service diagnostic procedures, since most procedures depend on a comparison with the initial records of a new transformer.

This type of testing should reveal design and manufacturing flaws. For flaw detection in design, the impulse test, heat run test and load and no-load loss measurement test are done. In relation to manufacturing flaws, for example, the induced voltage test with PD measurement is made. This tests will be the reference data for future measurements such as DGA, tanδ and winding frequency response.

Below is a test sequence, made by Efacec (after short-circuit testing) divided by days of a 36MVA 62.5 / 21 kV-ODAF-YNyn0 transformer from the Électricité Réseau Distribution France (ERDF).

Day 1

- Physico-chemical analysis of the oil
- Measurement of the insulation resistance and insulation of the magnetic circuit
- Measurement of the capacitance and tan δ of the windings
- Measurement of ohmic resistance of windings for all taps.
- Measurement of the transformation ratio and phase shift control for all positions
- Measurement of the ratio and polarity of current transformers.
- Load test with loss measurement and no load current with 0.9, 1.0 and 1.1 x Un with measurements of the harmonics of the no-load current.
- Measurement of load losses and short-circuit impedance for extreme and main taps
- Measurement of zero-sequence impedances for extreme and main taps

Day 2

- Analysis of gases dissolved in the oil
- Lightning shock test on line terminals (LIC on the HV side and LI on the LV side) and neutral (LIN)
- Applied voltage test (AV)
- Induced voltage test with measurement of PD (IVW + IPVD)

Day 3

- Analysis of gases dissolved in the oil
- ODAF refrigeration stage heating test
- Analysis of gases dissolved in the oil
- Heating test - Degraded regime of refrigeration
- Analysis of gases dissolved in the oil
- Measurement of noise level (with spectrum per third octave).
- Measurement of the power consumed by pumps and air-conditioners.

Day 4

- Testing of auxiliary circuits
- Verification of the dielectric strength of the insulation interposed between the tank and the earth or between the tank and the devices to be electrically insulated from the tank
- Paint control, dimensional and visual
- Measurement of short-circuit impedances per phase at low voltage.
- Frequency response measurement (SFRA)

3.2.1 Remarks

One of the first day, tests are directly related to the operational performance of the transformer. If the transformer is in operation, losses occur. Thus, the no load losses test is important for economic operation. This test is also used in the heat test.

The measurement of these losses depends on the voltage waveform and frequency. Thus, the voltage waveform should be sinusoidal and at rated frequency. These waveforms can be compared to identify future disparities.

As mentioned, insulation is one of the main constituents of a transformer. Insulation weakness may lead to transformer failure. To ensure effectiveness of the insulation system, dielectric test is confirmed. However, the power frequency withstand test alone is not adequate to demonstrate the dielectric strength of a transformer.

The lightning test, thus complements other tests, allowing the understanding of the insulation's behaviour when different waves are used.

PDs are dielectric discharges located in a partial area of a solid or liquid electrical dielectric insulation system under high-voltage field stress. These discharges lead to deterioration of the insulation which can lead to transformer failure.

The measurement of the PD will determine if there are partial discharges above a certain value at a pre-defined voltage. The voltage values in which the PDs start and stop are defined by increasing/decreasing the applied voltage as well as the strength of the PD at a given voltage. These values will be collected and can be used in future comparisons.

The gas dissolved analysis in the oil allows the knowledge of the gases and their quantities in the oil. This information will allow, later, to perceive if there are abnormal thermal and electrical stresses that would lead to changes in the quantities (see section 3.3.1). In this way, it would be possible to obtain information on the trend of deterioration in the health and life of the transformer.

Regarding the heat test, the transformer is energised to generate core losses. These losses would be considered the losses of moment 0 and, like the other data obtained, would be compared with subsequent moments.

The measurement of the power consumed by pumps and air conditioners would serve as a comparison term for future diagnoses as well.

On the fourth day, the verification of the dielectric strength of the insulation provides data corresponding to its initial value, so when an analysis of its strength is carried out, in the event of a discrepancy, it is necessary to verify what happened.

In relation to paint control, the values of the thicknesses will be annotated for later use as a comparison for future maintenance.

Finally, the Sweep Frequency Response Analysis (SFRA) will allow comparison between measures collected in several stages and in identical transformers, as well as comparing transformer measurements in the acceptance test phase. It will enable the detection in the future if the transformer core or windings were displaced, the deformation or failure in the core, collapse of the partial winding, breakage or loosening of the clamp connections, short circuits, open winding conditions.

Through this example, it was possible to verify the quantity of potential data that can be collected. From waveforms resulting from certain tests to numerical values like losses to gas types and quantities. These initial data establish the first stage and will result in the creation of the transformer digital twin.

3.3 Key parameters

Currently, monitoring certain parameters allows for timely corrective maintenance. The challenge is to balance the functions of the monitoring system with their cost and reliability, with the value they bring. To achieve an effective monitoring system at a reasonable cost, it is necessary to define some key parameters. The selection of these parameters should be based on failure statistics and consequences of these failures. However, it will always be up to the customer to define what he considers important to be monitored.

[43] results from the collection of 964 large failures occurring within a total population of 167,459 transformer years, provided by 56 concessionaires in 21 countries.

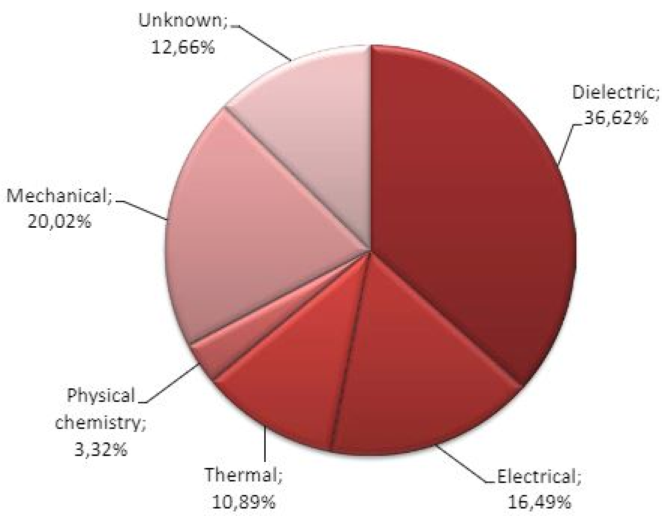

Figure 3.4: Failure mode analysis based on 964 major failures [43].

In figure 3.4 it is possible to verify that the most common failure modes were dielectric, mechanical, electrical, of unknown cause and thermal. Thus, given these percentages, there are certain parameters of transformer components that need monitoring.

Monitoring of parameters such as dissolved gases in oil, moisture and oil temperature is key. The monitoring of the dissolved gases was developed in section 3.2 and section 3.3.1. The oil temperature needs to be measured continuously in order to maximise the life of the transformer. Information such as ambient oil temperature, load (current), fan/pump operations are used to determine the hottest spot (section 3.1.2.2) and to manage the general temperature conditions.

Winding temperature monitoring is critical. There is a correlation between the winding temperature and the normally expected life of a transformer. As mentioned in section 3.1.2, the highest winding temperature is one of the factors that will limit the load of a transformer [40]. Long exposure to high temperatures leads to loss of mechanical strength of insulation materials. This results in the tearing and displacement of paper and dielectric breakdown.

Ageing-related deterioration processes are enhanced by thermal and voltage stresses. Increased temperature, oxygen, moisture contribute to the degradation of the insulation.

During some loading peaks, high moisture can result in water vapour bubbles. These bubbles lead to the reduction of the dielectric strength of the insulating liquid, resulting in dielectric failures. These problems can take years to develop, but might appear unexpectedly. Loading peaks can be monitored through voltage and load current are considered key parameters. Thus, the maximum load depends on the temperature at which the transformer and its accessories are exposed without excessive loss of life. Monitoring will alert users by providing a means to analyse the thermal performance of the transformer.

By combining moisture and hot spot and the load history of the transformer, it is possible to determine the degradation state of the paper. This knowledge is important because if the paper is in a state of high degradation there are no guarantees regarding the insulation capacity of the transformer.

In this work, it is intended to analyse the data from the activity of the transformers to make the analysis described above, to understand how the predictive maintenance would benefit in economic terms the company that owns the transformer or set of transformers, since it saves manpower and unnecessary inspections and also reduces the unnecessary shutdowns of the system [23].

3.3.1 Condition monitoring techniques

Faults occurring in the transformer are generally difficult to locate and diagnose due to the complexity of the transformer's internal structure. Thus, a set of multi-parameter condition monitoring techniques have been used to provide significant information for the diagnosis of faults and their possible location. This type of techniques is essentially used in insulation systems and checking the integrity of the winding.

These techniques presented in figure 3.5 will be explained below and will allow the monitoring of the transformer allowing a possible extension of its life time.

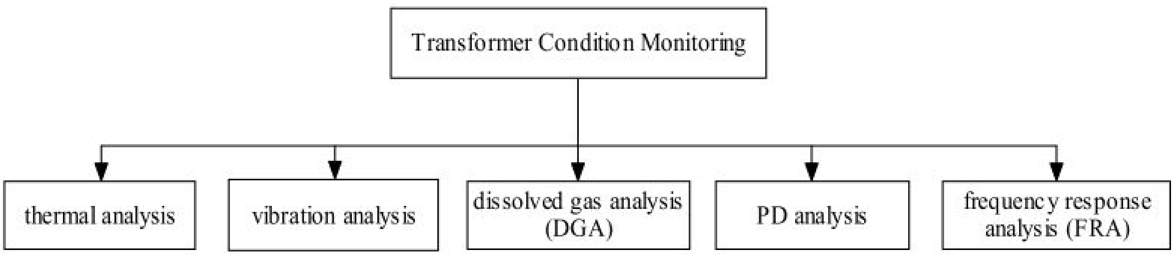

Figure 3.5: Transformer condition monitoring techniques [44].

1. Thermal Analysis

   Through a thermal analysis to the transformers it is possible to collect information about its state allowing the detection of discrepancies and failures that may occur. Most faults change the thermal behaviour of the transformers [23].

The critical parameter to be analysed in this situation corresponds to the hot spot temperature (HST). This parameter corresponds to the maximum temperature in the windings of the transformers.

The standards IEC 60076-7 and IEC 60076-2 are used to analyse this parameter.

2. Dissolved Gas Analysis

   This type of analysis is one of the most generalised forms of monitoring the insulation condition. Through the type of gases present and being generated, their concentrations and their production rate, it is possible to diagnose faults that might be about to happen.

   Combustible gases are produced when certain materials present in the transformers undergo thermal or electrical stresses.

   An increase in the concentration of certain gases, a combination of the variation of certain types may indicate that something in the transformer is not working as expected, in fact it possibly be a sign that a transformer will suffer partial discharges soon, for example [23]. This type of analysis can be done for a given gas, for a set of them, however as the size of the information increases, the cost of the monitoring equipment will increase.

   The method that will be used to explain this type of analysis is described in the standard IEC Standard 60599 and is called Duval triangle method.

Duval Triangle Method

The Duval Triangle uses three hydrocarbon gases only (CH_4, C_2H_4 and C_2H_2). These three gases correspond to the increasing levels of energy required to generate gases in transformers that are in operation [45]. This method is indicated in the figure 3.6. In addition to the 6 individual fault zones indicated in the table 3.2, there is a DT zone which corresponds to a mixture of thermal and electrical faults in the transformer.

Table 3.2: Examples of faults detectable by Dissolved Gas Analysis [45]

Symbol	Fault	Examples
PD	Partial Discharge	Discharges of the cold plasma (corona) or type in gas bubbles
D1	Low Energy Discharge	Partial discharges of the sparking type
D2	High Energy Discharge	Discharges in paper or oil resulting in extensive damage to paper or large formation of carbon particles in oil, metal fusion
T1	Thermal Fault, <300°C	Paper turning brownish (200°C) or carbonised(300°C)
T2	Thermal Fault, 300°C<700°C	Carbonization of paper, formation of carbon particles in oil.
T3	Thermal Fault, >700°C	Extensive formation of carbon particles in oil, metal coloration (800°C) or metal fusion (1000°C)

The three sides of the triangle are expressed by coordinates (x,y,z) representing the gas proportions, from 0 to 100% for each gas. The calculation begins with the determination of the concentrations through DGA results[46, 47, 45].

The sum of the three values x + y + z, in ppm, is made. Then, the relative proportion of the three gases is calculated. The sum of the proportions must be between 0 and 100%. The plot of the three points provides a point in the triangle and will allow the identification of the fault provided by DGA results.

$$x = C_2H_2[ppm], y = C_2H_4[ppm], z = CH_4[ppm] \tag{3.4}$$

$$C_2H_2 = 100 \times \frac{x}{x+y+z} \tag{3.5}$$

$$C_2H_4 = 100 \times \frac{y}{x+y+z} \tag{3.6}$$

$$CH_4 = 100 \times \frac{z}{x+y+z} \tag{3.7}$$

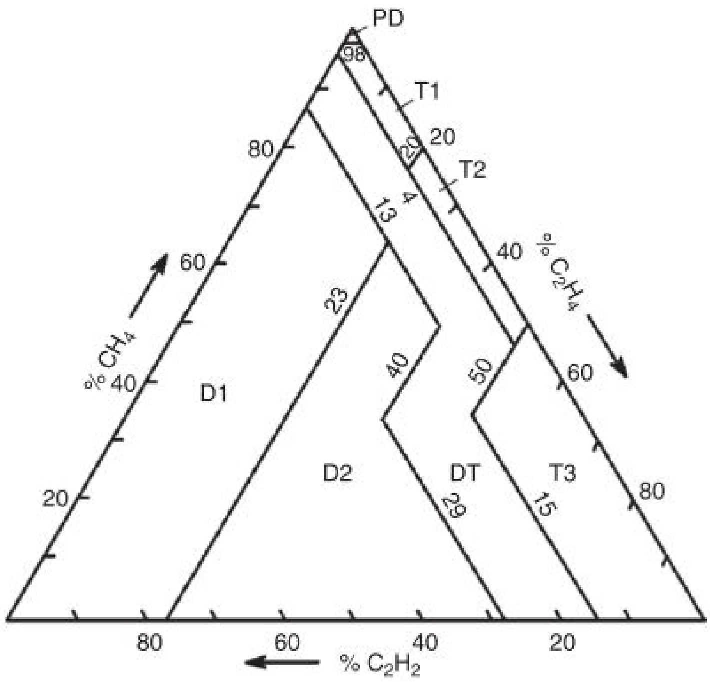

Figure 3.6: Coordinates and fault zones of the Triangle [46, 47].

Faults in paper are considered more serious than oil, because paper is situated in areas of high electric field and their destruction can lead to short circuits and severe arcing . However, faults in paper are less common than oil faults. Thus, its detection through DGA or other means is important [45].

Faults in paper can be detected through DGA through the CO_2/ CO ratio. Values < 3 indicate failure and the paper is rapidly degrading might carbonise. However, since there is CO and CO_2 in the oil (except in the early years), special attention to interpret the values is needed. Values > 10 indicate thermal failures in paper at temperatures <150°C, but only affect paper in the long run [45].

This method has the advantage that allows visual analysis. It follows the evolution of the faults from the moment they are still harmless until the moment they can produce major setbacks.

According to [46, 47], T3 failures in service tend to relate to hot spots in oil and T1 and T2 failures in paper, unless stray gassing oils are used. Regarding PDs potentially dangerous to the transformer, they are detected by DGA but can remain undetected.

The accuracy of DGA diagnosis is an important factor. The results always present a percentage of error, being higher or lower. These deviations occur especially at lower concentration levels [45].

By doing an analysis of the figure 3.6, it may happen that, given a percentage of error, a value can cross two or more zones of the triangle. This result may lead to a misdiagnosis which, for example, an arcing problem can be diagnosed as a less severe thermal failure.

Thus, users of the DGA diagnosis should be aware of inconsistencies and uncertainties in the results and should check the accuracy of their laboratories.

3. Frequency Response Analysis

   One of the analyses that can detect possible deformations and movements inside the transformer (in the windings as well as in its core) is called FRA. This type of analysis allows to know the condition inside the transformer using non-intrusive techniques.

   Although it is a relevant technique, there is the problem related to the internal complexity of the transformer, because when a frequency sweep is made the internal components are mixed leading to an aggravated difficulty to distinguish each component individually.

   When the mechanical structure of the power transformer and its windings are subjected to high fault currents, the mechanical stress observed is high.

   The causes for winding deformation may derive from loss or reduction of clamping pressure and short circuits [32, 48]. Ageing of paper can also cause winding deformation.

   Thus, despite promoting the detection of internal mechanical failures the results are affected by several factors leading to uncertain conclusions.

4. Partial Response Analysis

Partial discharges are one of the main sources of damage to the insulation system of transformers. In this way, it is required to monitor this type of discharges, which are done in a non-destructive way. Partial discharges can be detected and measured using Ultra High Frequency (UHF) sensors.

The method using UHF sensors proves to be effective in detecting the location of the partial discharges origin when compared to other methods because of the its lower signal damping and low noise [49].

A partial discharge increase leads one to believe that there are insulation problems in the transformer or that may be about to happen.

5. Vibration Analysis

   The use of this technique is useful to understand the condition of the transformer and only started to be used recently.

   Through the signature of the tank vibration it is possible to understand the condition of the active part of the transformer [50] and it is also used to assess the health of the OLTC [51, 52].

   The vibration of the tank consists of two types of vibration: core vibration and windings vibration [50]. Signature vibrations, which are collected and measured by accelerometers, propagate through the oil until they reach the walls where the sensors are placed.

   The continuous wavelet transformation was used in [51, 52] (with positive results), to analyse the vibration bursts generated by the OLTC in operation, due to its ability to extract the useful characteristics of the non-stable and fast transient signals.

   However, this technique has yet to be further developed, especially in the evaluation of the OLTC condition, so that it is possible to proceed to the evaluation of other components of the transformer.

3.4 Transformer Monitoring Architecture Systems

3.4.1 Architecture Description

Continuous monitoring has become an integral part of power transformers as it enables performance assessment and safety of the operating conditions of the transformers.

Although it is an increasingly common practice, continuous monitoring is associated with sensor selection, its functionality as well as system monitoring architecture and varies among users.

This variability depends on a set of factors such as importance, size, age and condition of the transformer [27]. In addition, the information technology infrastructure available will influence the decision to choose an architecture.

Other aspects that may play an important role in choosing an architecture are related to the company's strategic decisions and economic issues.

For example, a large utility operating a large fleet of transformers, may want to invest in an application that includes the entire fleet of transformers. However, for a smaller utility, a less networked architecture installed at the primary level with an access for remote information visualisation and interactive operation might be more reasonable [27].

Although there are variations, the common architecture of a Transformer Intelligent Condition Monitoring (TICM) system can be seen in terms of [27]:

- **Physical architecture**: contains system components (sensors, IEDs, database servers and data processing units) as well as their physical location

  Regarding the physical location, components may be in transformer control cabinets, in monitoring cabinets installed near the transformer or can be located physically in the control area of the station.

- **Communication architecture**: describes the hardware and software used to operate the data and information flow between the components of the physical architecture and the entire system

- **Data and information architecture**: necessary input/output information, and its interrelationship

Since there is a variety of continuous online monitoring architectures, Figure 3.7 shows a generic view of a TICM system independent of technical details that vary from user to user.

As you can see from Figure 3.7, monitoring systems will incorporate a set of features ranging from acquisition, consolidation, data storage to analysis and diagnostic tools.

In this final step, the information is visualised through a Human-Machine-Interface (HMI) workstation or any computer on the network with access to the monitoring system.

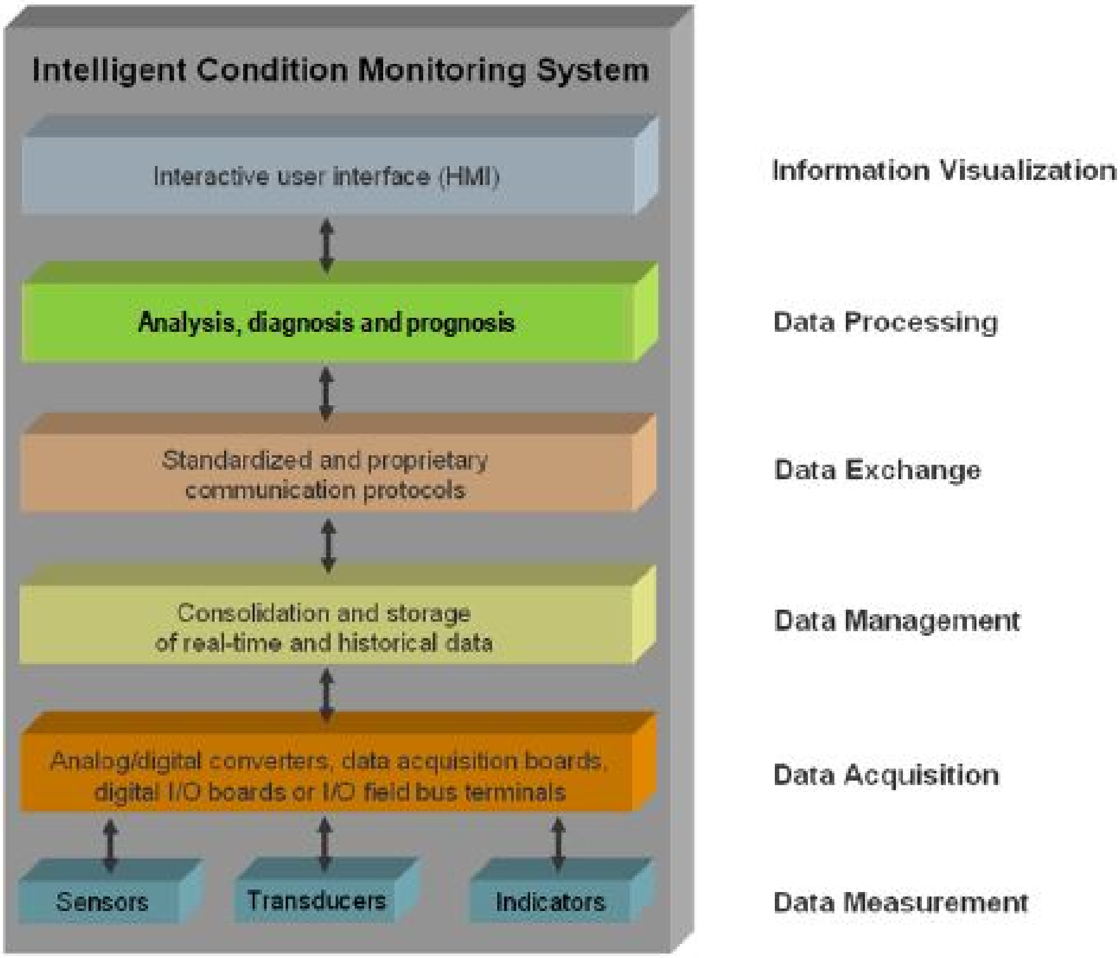

Figure 3.7: Generic view of a TICM system [27].

3.4.2 Comprehensive System

The functionality and intelligence of an online monitoring system can be implemented in a number of ways. It can be implemented by a single IED per transformer, designed on a modular basis and allocated to several interconnected IEDs that cooperate, or the functionality of the IEDs is combined with an installed monitoring server [27]. Another way would be for a group of transformers to be connected to a single IED.

Due to the architecture of this type of systems, the acquisition of multiple parameters will allow an analysis and assessment of the health status of the transformer allowing the asset manager in decision-making. This multiplicity of data provides correlations between relevant data not only of the transformer but also from other transformers.

There may also be another system in the central system that performs data analysis, diagnosis and prognosis from a correlation with other off-line data (periodic inspections, maintenance records) [27].

3.4.3 Data Management and Communication

In order for these data to reach the asset manager, it is necessary that the components of the on-line monitoring system to communicate efficiently and be able to share measured and analysed data through internationally standardised communication protocols interfaces.

The higher the level of standardisation of interfaces, the greater the possibility of expandability, interoperability, compatibility and having a more extensive monitoring system [27].

This growing data network between different processes, devices and control centres allows, in real time, the exchange of information and potential creation of remote monitoring centres. Through such solutions, any type and amount of data can be accessed and sent at any time to a remote monitoring centre to be viewed, analysed [27]. This means that, at the corporate level, a corporate monitoring server and corporate database are needed.

An architecture solution based on data processing, storage servers need a strong and flexible communication infrastructure. The development of wireless technology can play an important role in the physical architecture of the monitoring systems, allowing simplification of wiring and increasing the flexibility of the system [27].

Combined with this development, challenges related to cyber-security are increased as data will be collected and transferred to the IED or even directly to the network.

3.5 Transformer Monitoring Systems

Nowadays, it is possible to recognise the information potential in the transformers considering the data that could be collected from the available classical systems. Thus, there is a need to convert the data inputs (factory tests, inspections and diagnostics, transformer history, data continuously collected) into advantageous and intelligent outputs that will allow the owners of the transformers to make the best technical and therefore business decisions [27].

However, for this to happen, there is the need to have a system that performs this kind of monitoring. These systems allow a set of inputs to be converted into valid information in a short period and regardless of their volume.

A system of this type besides having intelligent features in the storage component should also have it in the analysis chapter. In addition, it should be a source of information and data for a group of people from the operations staff to the staff involved in maintenance.

Thus, we are gradually moving from a reality in which we merely monitored to a point of being able to have the complete and continuous knowledge of the operational condition and the state of the fleet of transformers. In this perspective, the current market now offers plenty of sensors, IEDs, on-line continuous monitoring systems, analysis algorithms and software systems for condition evaluation that will help its users in decision making [27].

In this section, a set of monitoring systems that are currently on the market will be presented.

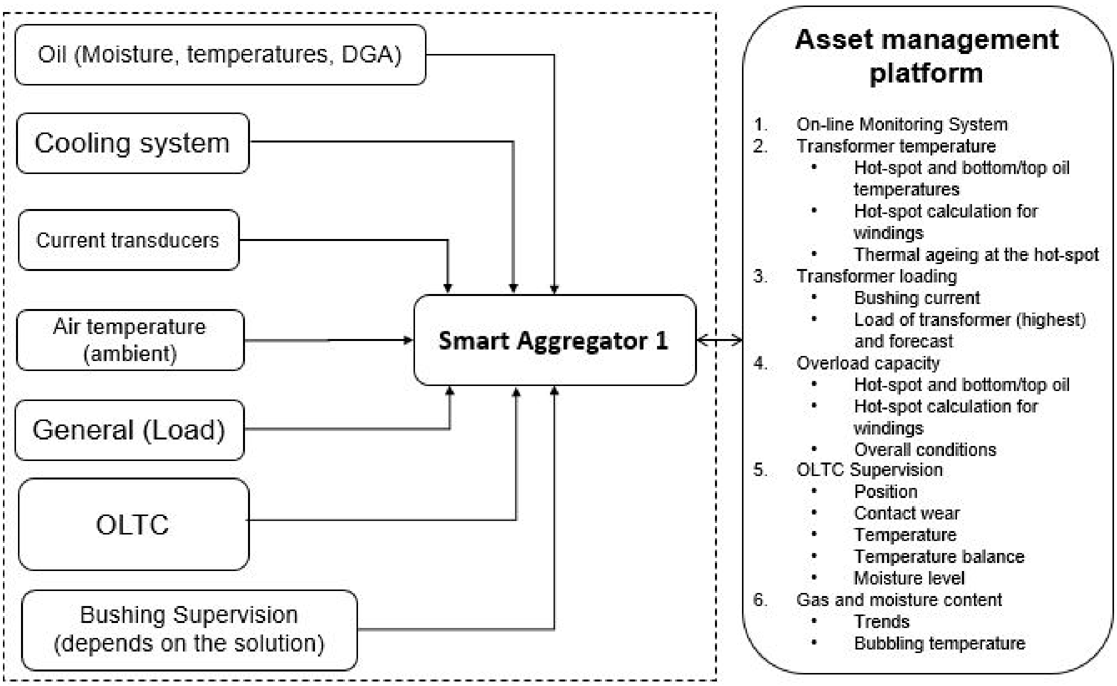

Figure 3.8: Monitoring System 1

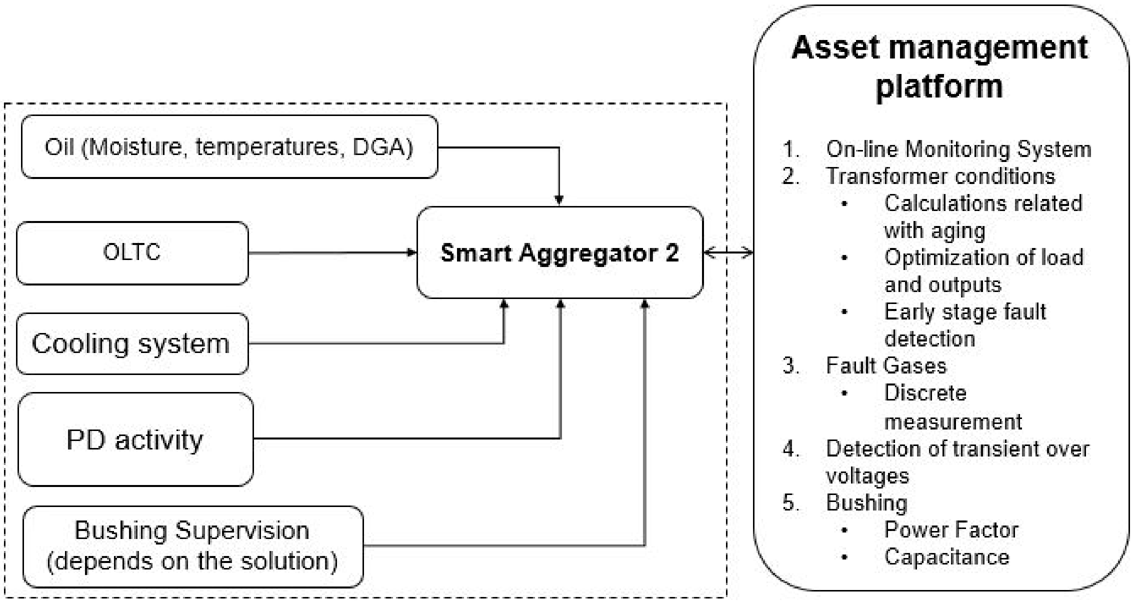

Figure 3.9: Monitoring System 2

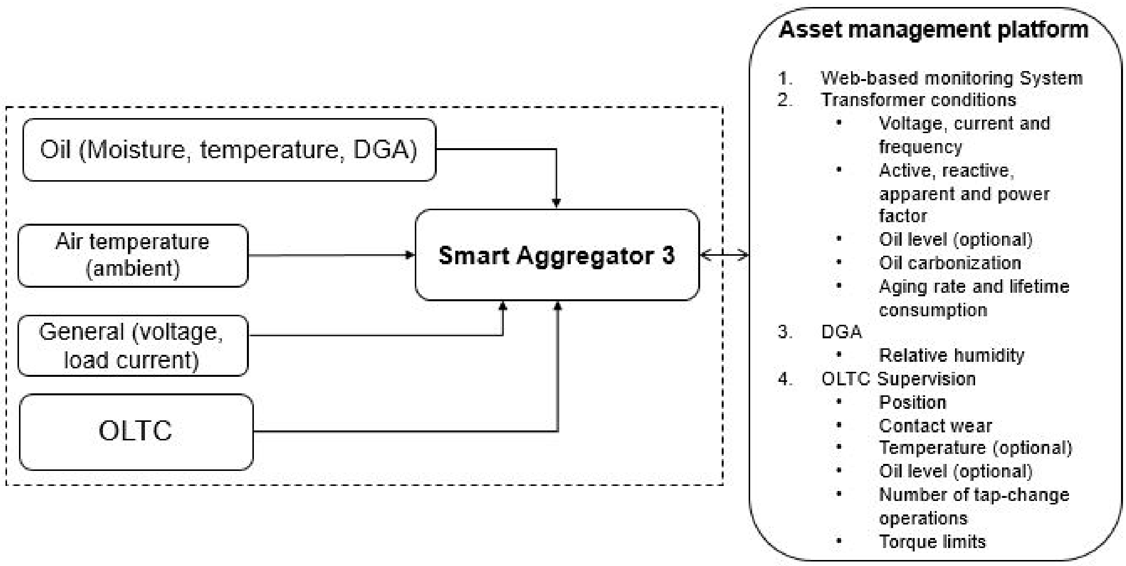

Figure 3.10: Monitoring System 3

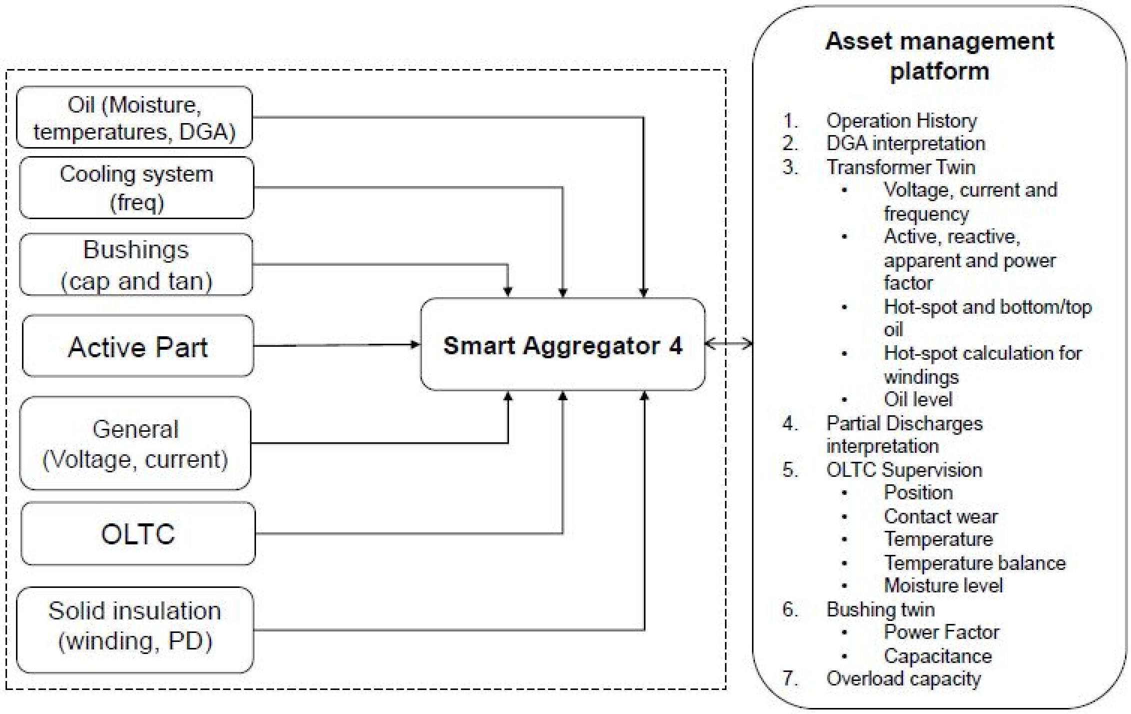

Figure 3.11: Monitoring System 4

Remarks

Through the analysis of the on-line monitoring systems, system 3.8 to system 3.11, it is possible to verify that they all allow monitoring of oil (moisture, temperature and DGA) and OLTC. Only system 3.10 does not allow bushing monitoring. In relation to the cooling system, only system 3.10 does not have this option. In terms of more general monitoring, such as a load current, only 3.9 does not have this functionality. Finally, some systems monitor the PD activity (system 3.9 and system 3.11) and the ambient temperature (system 3.8 and system 3.10).

The oil, given its dual function of cooling agent and insulation needs to be monitored in terms of its moisture, temperature and gases that are dissolved in it. As noted in section 3.1.5, as time goes by, oil degrades by losing its properties and its timely detection allows for failure modes to be prevented. The increase of gases can be detected through the DGA diagnosis and will allow the indication of high temperatures in the transformer or that discharges occurred. With regard to the sensor that measures moisture, through that it is possible to infer oil quality. Increased moisture means an increased likelihood of flashover between windings.

Regarding OLTC sensor, monitoring it will allow to know when the switching mechanisms begin to get worn out. This monitoring is done through information such as number of tap-change operations, position. If it is not done, a interruption of current may occur which will lead to arcing leading to the production of gases.

As mentioned earlier, bushings are not monitored only in system 3.10. This function present in other systems allows the capacitance measurement and the dissipation factor to determine the bushings isolation condition or condition between windings. Changes in capacitance indicate mechanical displacements of windings or partial breakdown of bushings.

The cooling system will be monitored in order to verify if the heat resulting from the transformer's operation is dissipated. A transformer operating $10°C$ above its rating reduces its lifetime by half [29]. Hence, it is imperative to detect early problems in this system.

PD activity, although not monitored in all systems, can be inferred through the presence of certain gases that provide this type of discharge (see section 2). Therefore, this sensor is not present in all systems. Their presence exist to correlate with data taken from other sensors.

Like the PD sensor, ambient temperature sensor is used to draw conclusions along with other sensors (see section 3.1.5 and 3.1.6). Ambient temperature assists in cooling the transformer and it is one of the parameters used to calculate the hot-spot temperature (section 3.1.2.2). The fact that this functionality is not as important as others means that not all systems have this sensor.

In conclusion, it is possible to verify that there are some sensors that given their relevance are used in all systems and others that that are not used. It should be noted that the choice of optional sensors for certain systems increases their cost. It is up to the client to know what he is interested in measuring with what he values the most in the transformer. If, for example, he considers bushings are not so important, he will not acquire a system that has this sensor.

3.6 Transformer Assessment Indexes

An asset manager is responsible for a group of transformers, which provide a large amount of data, needing to determine which transformers require attention. It is given a score system based on only a part of the information or the entire information.

Through this system, it is possible to create a ranking resulting from the assigned scores allowing the identification of the transformers that would most benefit from intervention or action.

The Transformer Assessment Index (TAI) can be developed to identify which transformers are most in need of intervention. An index used to identify this situation is called the Health Index (HI) and will be developed in the next section.

Alternatively, managers can create a large set of TAIs that in addition to indicating which transformers would benefit from repair, also those that could require non-essential maintenance, refurbishment or replacement.

In this section, it is defined the health index, the probability of failure rate and remaining life time. In addition, different methods for the development of a TAI are discussed with advantages and disadvantages being pointed out.

3.6.1 Health Index

When a transformer begins its operation, its insulation begins to undergo thermal stresses that result in its deterioration over time. In addition, at the same time, it can also experience extreme stress and internal damage to its main components due to failures that occur on the load side [53]. Since both windings and insulation are inside the transformer, it is economically unreasonable to carry out direct inspections. Thus, there is a need to use an indirect set of tests.

There is a methodology that combines information from complex conditions to provide a single numerical value called HI [54].

The design of an HI requires three steps [55]:

- Identify the factors that influence the condition of the asset
- Establish the correspondence between the possible states of each factor for a score on a common scale
- Estimating the relative importance of the factors.

This numerical value does not reflect the status of any particular part of a transformer with respect to repair, it does represent the level of long-term degradation, a condition not easily determined by routine inspection [56, 17, 57].

It is a metric used in asset management to reflect the condition and state of degradation and ageing of an asset [26]. It is an easily understandable value, included on a numerical scale, which can be used to make an objective comparison between assets or a reference value.

To build a HI model for an asset is necessary to consider operating state, field inspections, component test targets, and other existing information about the asset to obtain an objective value that represents its overall condition [58, 59].

A well-developed HI Model should have the following characteristics [60]:

- The index should be indicative of the suitability of the asset for continued service and representative of the overall asset health
- The index should contain objective and verifiable measures of asset condition, as opposed to subjective observations
- The index should be understandable and readily interpreted

This index provides information that identifies which transformers are near their end-of-life, including those that are effectively at the end of their life and those that represent a generally high risk of failure [56, 57].

In this way, it is possible to determine which transformers require immediate investment, refurbished or replacement, which will need to be refurbished or replaced soon, but not immediately and those that are in good condition and need no action [17].

The HI can be very useful in asset management. If its algorithm is well formulated, its application to existing assets provides an indication what should be considered when prioritising, allocating resources and identifying potential investment opportunities.

3.6.2 Failure Rate Probability

To evaluate the reliability of an asset, it is necessary to calculate the probability of a failure. This indicator represents the probability that an asset will suffer a general failure, making it incapable of fulfilling its function, and it may not be possible or economically worth to repair it.

This methodology corresponds to a line of research related to statistical analysis. Statistical analysis of the lifetime of an asset comprises collecting data, selecting an appropriate distribution model, adjusting the data to the model, and finding the determinant parameters.

This probability has a correlation with the HI of the asset, since it is expected that the probability of Failure of an asset increases with its degradation. If the HI is correctly formulated and represents a reliable estimate of the condition of the asset and its components, then it should make a significant contribution to the calculation of this probability.

Thus, a failure probability analysis should not be done isolated and always with HI since the power transformer depends on its operational condition. If a statistical analysis were made based on the age of the transformer, a generalisation could not be made for a transformer in operation [53].

If there is a detailed history of the failures that occurred in the assets then this can be used to calculate the probabilistic distribution of the types of failure and their causes, which gives a good estimate of the weights to give to each factor considered in the calculation of the probability of failure.

In this way, the individual importance of the possible causes of failure can be reflected. In addition, it can help identify transformers that have a high failure probability that cannot be easily repaired or replaced, and it is important to apply more sophisticated measures to increase the robustness of the system in which the active system is inserted, avoiding further damage.

3.6.3 Remaining Life Time

The remaining life time of an asset is an estimate of the time in which it is expected that the asset will continue to fulfil its function. This indicator allows asset management in a long-term horizon, since it lets the planning of refurbishment and replacement that allow a slowdown in the ageing process of the asset.

There is the need to study the life cycle of the asset, considering the individual history of the asset, the degradation processes that it undergoes during its operating time, the maintenance measures applied, the manufacturer's indications, as well as information collected by the variables that were previously selected and that are continuously monitored and that directly affect the asset.

One of the greatest difficulties of this type of analysis is the quick development of both characteristics of the assets and maintenance techniques, which reduces the importance of the study of the history of this type of asset. The knowledge and experience of engineers is vital to predict the effects of changes in the useful life of the asset and to make the necessary adjustments.

The calculation of this indicator can be done in two ways [26]. The first corresponds to an estimate of the obsolescence of the asset considering scenarios in which the asset can become outdated either by lack of reserve components, surpassed by another more profitable technology. In addition, the company may stop using the asset due to new legislation that causes the asset used not to meet the basic requirements.

The other methodology is a statistical analysis using parameters that have a correlation with the lifetime of the asset. A maximum lifetime is defined for the technology of the asset to which the age of the asset is subtracted. The operating conditions of the asset are considered as well as parameters that indicate its state of degradation leading to the remaining life time being shortened and thus it is possible to reflect the pressures to which the asset is and was subject. The result is the shorter remaining life time between the two estimates.

3.7 Methods of Calculating a Transformer Assessment Score

TAI can be presented through a single numerical value which allows an easy sorting of the transformer or through a colour code that will indicate the state of each transformer or a combination of the two forms.

3.7.1 Summation of individual failure mode scores

$$TAI = \sum_{i=1}^{N} S_{FM_i} \tag{3.8}$$

S_{FM_i} : score of an individual failure mode

The advantages of this method are the ease of the algorithm, transparency and weights can be added to the method if it is needed.

Regarding the disadvantages, the result may be optimistic, however there are low scoring failure modes that have been masked. Through nonlinear scoring, such as exponential scoring, they may no longer be masked.

3.7.2 Weighted average

$$TAI = \frac{\sum_{i=1}^{N} W_{FM_i} \cdot S_{FM_i}}{\sum_{i=1}^{N} W_{FM_i}} \tag{3.9}$$

W_{FM_i} is the weighting per failure mode S_{FM_i} is the failure individual mode score
N : total number of failure modes
Average weighting allows the calibration or weighting of failure modes, but may mask critical failure modes. In terms of disadvantages these are the same as the previous algorithm.

For each element of the linear relationship a weight is given according to its importance in evaluating the transformer [17]. However, for the final calculation, there are some variations in terms of weights. For example, there are some methods [56, 57] that give less weight to measures based on furans when compared to other factors such as winding resistance, dissipation factor, DGA.

An example that uses this algorithm is the case of DGA [56, 57, 61, 62, 63, 64]. The corresponding score is calculated as a weighted average of the scores of all the sub-parameters included in that parameter. In the case of DGA, these sub-parameters are the concentrations of the analysed gases in the oil.

The individual score of each gas depends on the concentration range to which the concentration value of each gas belongs. This score is assigned using a table constructed for each gas, where each concentration range corresponds to a score.

On the other hand, this weighting factor for each gas depends on the importance of the information extracted for each gas, to define the condition of the transformer [61].

Table 3.3 indicates an example of the S_i of each gas as well the W_i which corresponds to the proper weighting factor

Table 3.3: Scoring and weight factors for gas levels [ppm] [56]

	Score (S_i)						W_i
Gas	1	2	3	4	5	6	
H_2	$\leq$100	100-200	200-300	300-500	500-700	>700	2
CH_4	$\leq$75	75-125	125-200	200-400	400-600	>600	3
C_2H_6	$\leq$65	65-80	80-100	100-120	120-150	>150	3
C_2H_4	$\leq$50	50-80	80-100	100-150	150-200	>200	3
C_2H_2	$\leq$30	3-7	7-35	35-50	50-80	>80	5
CO	$\leq$350	350-700	700-900	900-1100	1100-1400	>1400	1
COH_2	$\leq$2500	$\leq$3000	$\leq$4000	$\leq$5000	$\leq$7000	>7000	1

3.7.3 Non-linear mathematical approach

$$HI = \sum_{n=0}^{k-1} x_n i^n \tag{3.10}$$

i : number base which is equal to or greater than the number of failure modes included in the HI
x_n : number of failure modes per category
k : number of categories included in the failure mode assessment

This type of approach avoids the masking of the worst failure modes. However, the scoring system is more complex, making the results more difficult to interpret. If weighting factors are used, it is necessary to modify the formulation to avoid the masking of failure modes.

3.7.4 Worst case approach

$$TAI = worst(S_{FM_i}) \tag{3.11}$$

S_{FM_i} : score of an individual failure mode

This algorithm [65, 66] as in section 3.7.1 and section 3.7.2 is easy to apply and transparent. In addition, it allows the worst mode of failure to be evidenced. However, the result may be too pessimistic and it is not possible to create a system of weighting failure modes.

This scoring system can be used in conjunction with 3.7.2, so the biggest problems are highlighted.

In [66], all estimates are combined. These estimates are combined through a function that combines the individual results that is designed considering the following principles:

- The chain is only as strong as the weakest link

- If all conditions are good, the asset's lifetime expectancy is increased

Regarding the first principle, a transformer can have multiple failure modes and sometimes a given fault can lead to more serious failures.

Thus, [66] considered the use of the worst-case approach for all critical-condition indicators since weighted average would mask/underestimate the likelihood of failure, hence overestimation of the transformer's health.

3.7.5 Count per category

The TAI is shown as a set of numbers, rather than an individual scalar value.
The number of failure modes assessed as being in each category is shown,for example, using a colour matrix.

This system has the main advantage of visually showing the total score of the transformer health evaluation, although the ranking in a transformer fleet makes the assessment more complex, since the result is not a single numerical value.

3.7.6 Machine Learning

For this calculation, a specific formula for the assessment score is not used, but rather using algorithms such as artificial neural networks [67] or fuzzy logic [17, 68] to determine the health condition of the transformer.

The use of these techniques may bring new correlations between indicators and failure modes allowing an improvement in index quality. However, the algorithm is complex and a large set of data is required for the system to be designed and to be reliable.

Chapter 4

Power Transformer Health Indexing: Comparison between models

In this section, a set of models for calculating health indexes will be presented and analysed. Firstly, it is explained the model structures, the necessary input data, calculation formulas and how the result is presented. Subsequently, a comparison will be made between models using a real case so that conclusions can be drawn.

The purpose of these models is to simplify the work of asset managers. The output will indicate which assets are at the highest risk, allowing decisions to be made regarding maintenance, refurbishment or replacement/reinvestment.

4.1 Hydro-Québec

4.1.1 Description

This model presents a concept called apparent age. This notion helps in the comparison of assets allowing the calculation of the equivalent age of the assets based on their condition. After this calculation, the probability of failure of the asset is estimated, allowing its inclusion in a risk matrix in which decisions are made.

4.1.2 Input data

Hydro-Québec points out that during the development of the health index it is necessary to establish the objectives of the health index. If, for example, its development serves to establish long-term investment priorities, immediate action would not be necessary when there were variations in certain data, since other processes would have a greater degree of importance.

It is necessary information of the existing transformers' fleet. Information that has been collected by condition assessment actions is usually the largest source of information. Other information such as corrective maintenance actions tracking, age at the time of transformers' scrapping are valuable information to include.

For Hydro-Québec there is a link between age and probability of failure or replacement. The age of a transformer is considered a global indicator of health that can compensate for the lack of information of other parameters used. So, age is an important parameter to consider.

Based on the data collected, Hydro-Québec decided to develop an indicator only if the information was available for the majority of the transformers in order to compare units on the same basis. Table 4.1 presents the input data used:

Table 4.1: Indicators used to estimate the Health Index [69, 70]

Nature	HI Parameter	Description
Vintages	Failure Rate of similar transformers	Transformers are divided into families. Each family is created based on specifications, manufacturer, age. Failure data is used to identify families with the lowest reliability
Active part	Solid insulation condition	Markers relative to the degree of ageing of the paper measured in transformer oil
	Dissolved Gas Analysis	Calculation based on the absolute values of the gases found in the DGA samples. Each gas has its specific weight in the final calculation. Also considered its trend over time
	Moisture content	Measured to estimate water content in the paper insulation
Oil	Oil tests	Oil quality is characterised by acidity, interfacial voltage, dielectric strength and power factor
Components	On-Load Tap Changer	Information regarding OLTC reliability and maintenance record
	Bushings	Information on bushing type, maintenance record and reliability
	Accessories reliability	Reflects the need for maintenance on accessories. Score derives from rate of corrective actions to correct accessory problems
	Gasket System Condition	Rate of corrective actions carried out to repair oil leaks

4.1.3 Assessment Methods

4.1.3.1 Statistical Estimates

Through the non-parametric Kaplan-Meier product limit estimator it is possible to examine how the survival and failure rate of transformers progresses with the age of the transformer. This method avoids biased assumptions regarding the shape of distribution of the variable's distribution (probability of failure) [71]. Its choice is also due to the fact that the data in the survival analysis are incomplete (right-censored) because there are transformers that are still in operation [69].

Through the use of this estimator, the current rate of failure and survival is produced as a function of age, allowing the selection of a parametric distribution. A comparison is made between parametric distributions of which their statistical properties are known. The most consistent distribution using curve fitting is the Weibull distribution.

4.1.3.2 Health Indexing

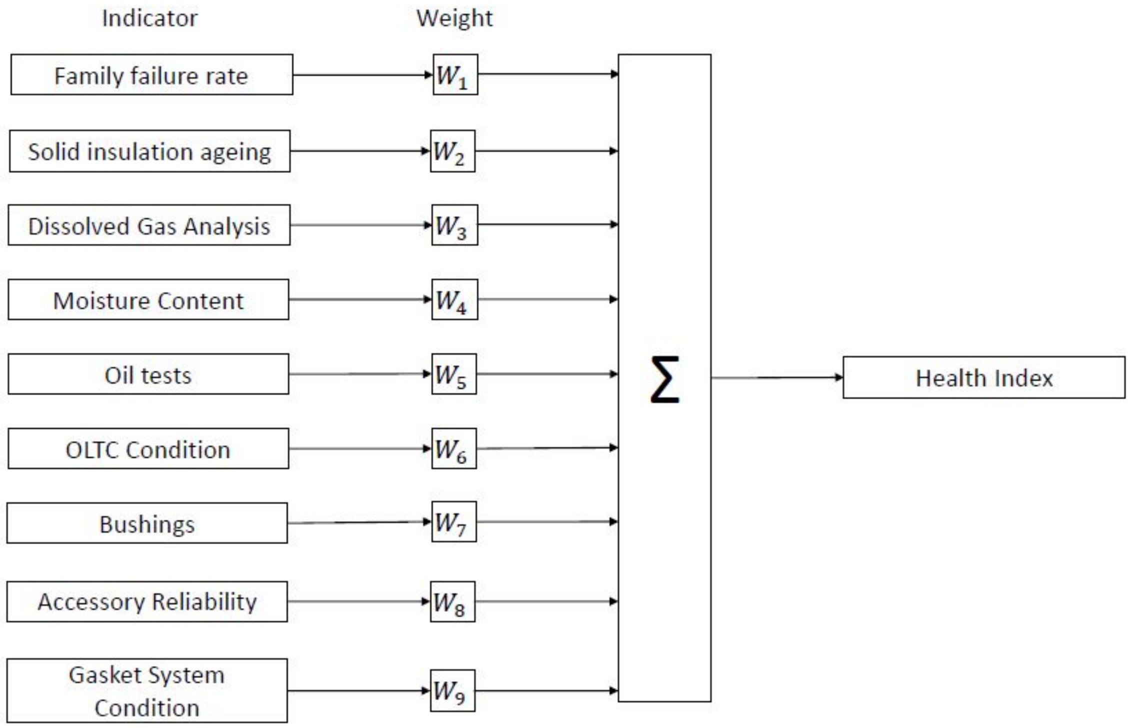

Figure 4.1: Schematic of the Hydro-Québec health index module [28]

After the data were selected, the next step corresponds to how the information will be aggregated in order to obtain the health index. As stated in section 4.1.2, there is a relation between health index parameters and age. Thus, it was necessary to find a way to group all these parameters into a global health index. The approach used is the sum of the weights described in section 3.7.2. The indicators have weights different from each other in the overall calculation reflecting their relative importance.

Generally, indicators whose condition is irreversible weigh more and the indexes that can be improved through maintenance actions have a lower weight. Table 4.2 describes the weighting factors applied to each indicator.

To score each index, there were two different approaches possible: linear score or exponential score. If the goal is to create a global index very sensitive to a poor condition (eg bad DGA) revealed by a specific index, then a nonlinear approach is preferred.

4.1.3.3 Output

The output of the HI model has a score of 0 to 50, where 0 represents the best possible condition. When transformer fleets are analysed, the score for each transformer can be plotted on a diagram where the age of the asset is found on the x-axis and on the y-axis the HI score. When a group of transformers is examined, it is possible to obtain a regression line that indicates the relationship

Table 4.2: Weight determination for health indexes [70]

Nature	HI Parameter	Weight
Vintages	Failure Rate of similar transformers	High – Irreversible
Active part	Solid insulation condition	High – May be very hard to improve
	Dissolved Gas Analysis	High– Irreversible
	Moisture content	High – Difficult to improve
Oil	Oil tests	Medium – Oil reclamation can improve
Components	On-Load Tap Changer	Low – Maintenance action can be done
	Bushings	Low – Relatively easy to replace
	Accessories reliability	Low – Maintenance actions can improve
	Gasket System Condition	Low – Maintenance actions can improve

between the average condition of the fleet with age. Units above the regression line are those in a poorer condition than average for units of their age.

An illustration of the output is given by figure 4.2. A regression line has been added to indicate the average condition of the fleet.

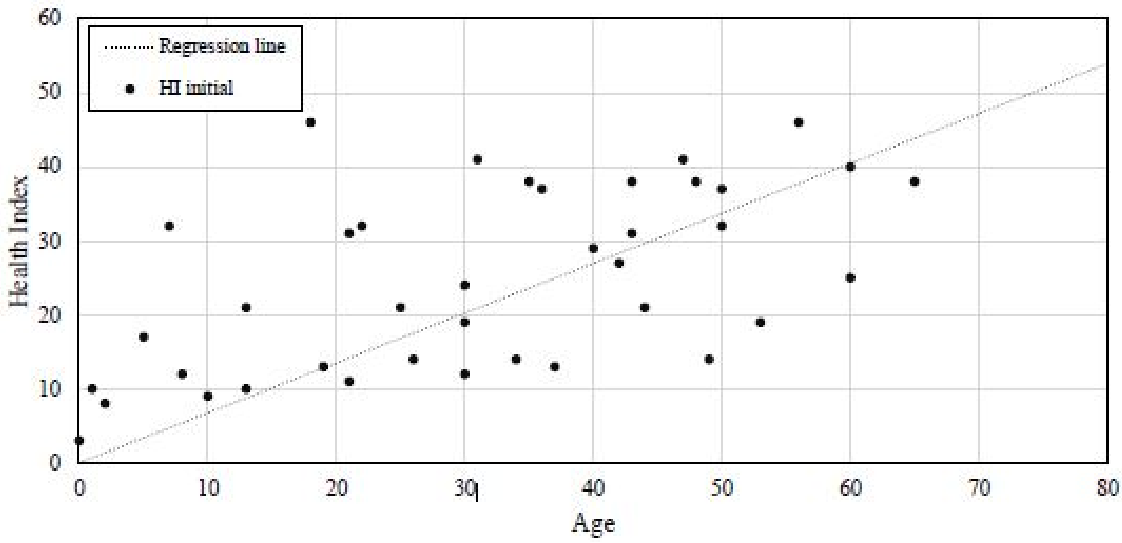

Figure 4.2: Average HI for each age group and the regression line [28].

Figure 4.2 shows an Average HI for each age group. From this example, it can be seen that an increase in age may not mean a worse HI. An example of this is the transformer with almost 20 years that has a HI near 50, that is, needs to be analysed briefly.

Apparent age calculation

Given that it is difficult to relate a health index score to probability of failure, the concept of apparent age is presented [69, 70, 53]. This idea is based on the idea that all assets receive an apparent age that is determined by the output of the regression line. The apparent age is the age that gives the regression line the same score as the health index in question.

The regression line can be written as follows: h(x)=a.x+b, where x is the asset's age, a is the slope of the curve and b is equal to 0 if the line passes through the origin [28]. An asset i with scoring health index h_i will have an apparent age of x_{app} according to equation 4.1:

$$x_{app} = \frac{h_i}{a} \tag{4.1}$$

This method can give large deviations between the actual age and the apparent age calculated. To avoid such situations, the HI estimates are first shrunk vertically between the limits of 10 years below and 15 years above the regression line [28, 69, 70, 53]. The upper and lower extreme values are located on the respective limit lines, while the remaining values are scaled between the regression line and the limit lines.

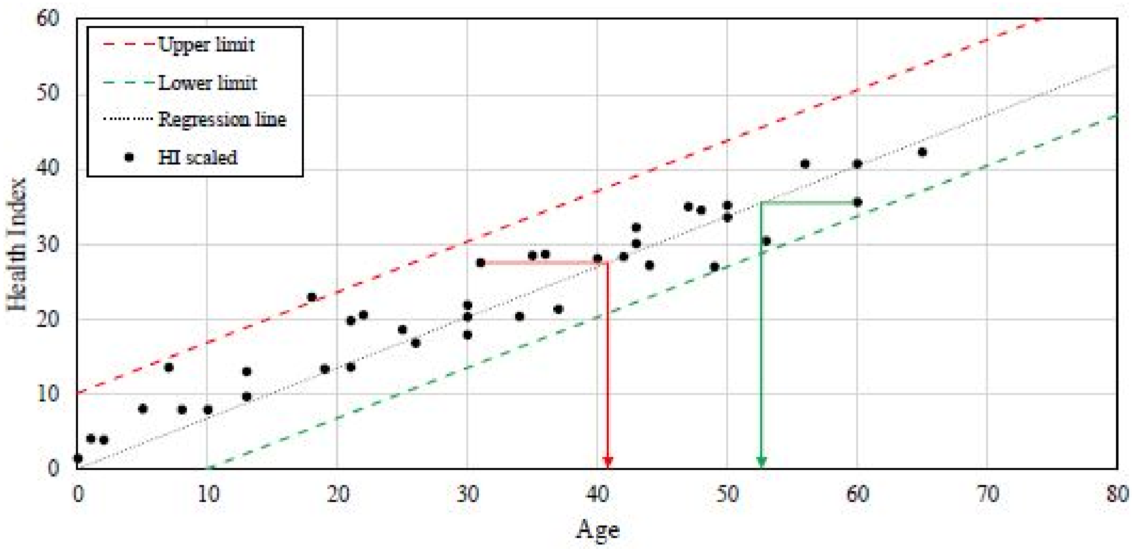

Figure 4.3: Apparent-age calculation for two units using their HI estimate and age [28].

Adjusting the age of two transformers, A (red) and B (green), based on their HI values are shown in figure 4.3. The HI of transformer B is below the regression line. So, age will be adjusted to a smaller value. This indicates that considering the tests performed, transformer B is in better condition than would be expected for a unit typical of its age. In this way, it can be moved to the age category respective to its condition [53].

On the other hand, transformer A is in a health condition worse than expected for its age category [53]. Thus, its age is adjusted to a greater value corresponding to its health condition.

When apparent age is determined (figure 4.3), it is possible to reevaluate failure/replacement risks. It is used to combine in conjunction with the failure rates obtained from the statistical average ageing model to estimate the probability of failure of an asset. Assets can then be positioned along the probability axis of a risk matrix. [28, 69, 70, 53].

Risk Matrix

The risk matrix is a 9 by 9 matrix (Figure 4.4). The probability values are linked to the apparent age of the equipment. The x-axis (probability) shows the failure/replacement rate based on apparent age and the y-axis represents the asset's importance in terms of the consequences of its loss.

After the limits are determined, the apparent age can be used to locate each transformer in the probability matrix of the risk matrix and the replacement priority can be given to the transformers with the highest risk [69, 70].

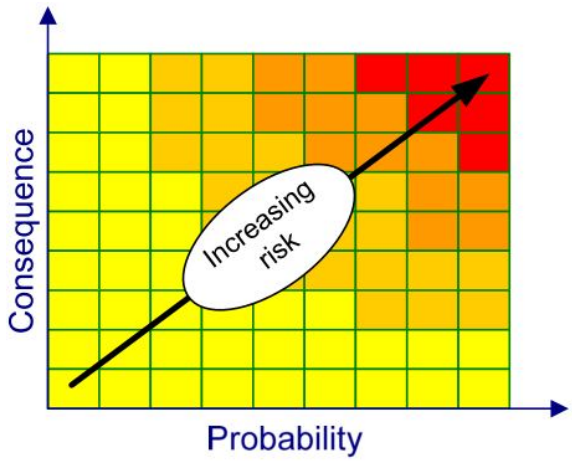

Figure 4.4: Risk Matrix [69].

4.1.3.4 HI confidence level

The uncertainty associated with each indicator used for HI calculation depends on the type and age of the data. When the confidence level is considered unsatisfactory, it may be possible to increase it by initiating condition assessment actions to obtain more recent or more accurate data to make a better decision. These individual HI confidence levels are then compiled to calculate a global HI confidence level [69].

The statistical distribution for the probability of failure will also be associated with an uncertainty that will affect the final evaluation.

4.2 Kinectrics-based model

4.2.1 Description

Kinectrics has proposed a system for assessing the overall condition of the transformer. The method uses service and diagnostic data as inputs and assigns scores to the different subsystems of the transformer through algorithms. This method does not contain statistical elements, but only focuses on the condition of the data. In addition, they provide a more detailed explanation of how the evaluation is conducted.

4.2.2 Input data

The model includes condition and service data as inputs in evaluating the condition of the transformer. The scheme of how this data is processed can be seen in A.3.

4.2.3 Assessment Methods

Different evaluation modules for each condition will be presented, including how different parameters are converted to a HI model score.

4.2.3.1 Dissolved Gas Analysis

The gas content in the oil is compared to the rating values of the table 3.3 and each gas gets a final score. From the concentration of these gases a Dissolved Gas Analysis Factor (DGAF) is calculated, using the equation 4.2:

$$DGAF = \frac{\sum_{i=1}^{7} S_i \times W_i}{\sum_{i=1}^{7} S_i} \tag{4.2}$$

where S_i is the score of each gas based on table 3.3 and W_i is the weight factor of each gas. The rating code starts with A as the best condition to E, which represents the worst situation. This type of coding is employed for the remaining factors.

The rating code begins with the letter A (best condition) and ends in the letter E (worst condition). This type of coding is used for the remaining factors.

Table 4.3: Transformer rating based on Dissolved Gas Analysis factor [56, 57]

Rating Code	Condition	Description
A	Good	DGAF<1.2
B	Acceptable	1.2≤DGAF<1.5
C	Need Caution	1.5≤DGAF<2
D	Poor	2≤DGAF<3
E	Very Poor	DGAF≥3

This assessment method does not serve as a diagnostic technique, but as a technique to evaluate the long-term quality of the oil. A reduction of HI is recommended if the rate of gas increase is greater than 30% in three consecrated gas samples or 20% in five consecutive samples of oil [56, 57].

4.2.3.2 Oil Quality

Like the determination of DGAF, an oil quality factor (OQF) is obtained by scoring the most important properties of the oil. These properties are found in table A.1. The OQF is calculated by equation 4.3, where S_i is the score of the different properties and W_i is the corresponding weight according to table A.1. A The final rating of the oil quality is obtained in a similar way to the DGAF.

$$OQF = \frac{\sum_{i=1}^{6} S_i \times W_i}{\sum_{i=1}^{6} S_i} \tag{4.3}$$

4.2.3.3 Furfural

Furan analysis can be used as a method to estimate the DP of the paper insulation. Based on the concentration of 2-FAL in the transformer oil, a score is given according to table 4.4. An alternative to the absence of data is to use age as an indicator for the winding insulation condition. However, Table 4.4 has no direct relationship between age and content of furanic compounds.

Table 4.4: Furfural test rating or age rating where test not available [56, 57]

Rating Code	Furaldehyde [ppm]	Age [years]
A	0-0.1	Less than 20
B	0.1-0.25	20-40
C	0.25-0.5	40-60
D	0.5-1.0	≥60
E	≥1.0	–

4.2.3.4 Power Factor

Power factor is a source of data to monitor both transformer and bushing condition.

In this model, the highest value is used to determine a score. The proposed scores are shown in table 4.5:

4.2.3.5 Tap Changer

In [56, 57] a method is presented to classify the the tap changer condition. The method is designed to differentiate three tap changer types (resistive, reactive and vacuum). The table Y proposes a scoring method for the DGA, however since most of the tap changers in Europe are of the resistor

Table 4.5: Power factor rating [56, 57]

Rating Code	Maximum Power factor [%]
A	pf_{max}<0.5
B	0.5≤pf_{max}<0.7
C	0.7≤pf_{max}<1.0
D	1.0≤pf_{max}<2.0
E	≥2.0

type only those values will be presented. The rating is based on the DGA result in the oil of the tap changer. The score is obtained in a similar way to the DGAF.

Table 4.6: Rating of the LTC based on Dissolved Gas Analysis [56, 57]

Gas	Score (S_i)				W_i
	1	2	3	4	
CH_4	≤50	50-150	150-250	≥250	3
C_2H_6	≤30	30-50	50-100	≥100	3
C_2H_4	≤100	100-200	200-500	≥500	5
C_2H_2	≤10	10-20	20-25	≥25	3

4.2.3.6 Load History

The load history is represented by the load factor (LF), which considers the load peak S_i of each month. The ratio between the monthly peak load and the rated loading S_B is calculated for each month. The number of cases in which the monthly peak load falls in one of the groups shown below is recorded. The equation 4.4 is used to calculate the LF of the transformer. The classification of the load history based on the load factor is obtained from Table 4.7.

- N_0: Number of instances where $S_i/S_B < 0.6$
- N_1: Number of instances where $0.6 < S_i/S_B < 1.0$
- N_2: Number of instances where $1 < S_i/S_B < 1.3$
- N_3: Number of instances where $1.3 < S_i/S_B < 1.5$
- N_4: Number of instances where $S_i/S_B > 1.5$

$$LF = \frac{\sum_{i=0}^{4}(4-i) \times N_i}{\sum_{i=0}^{4} N_i} \tag{4.4}$$

Table 4.7: Load Factor rating codes [56, 57]

Rating Code	Load Factor
A	LF $\geq$ 3.5
B	2.5 $\leq$ LF <3.5
C	1.5 $\leq$ LF <2.5
D	0.5 $\leq$ LF <1.5
E	LF $\leq$ 0.5

4.2.3.7 Maintenance Data

A rating system has been developed based on the maintenance orders issued during the last five years for the transformer and its accessories. These service orders are counted and compared to the criteria in table 4.8. If there is no maintenance order in the years stipulated for any of these factors, the condition rating will be "A", and if it is greater than 6, it will receive an "E" rating.

Table 4.8: Rating criteria based on number of corrective maintenance work orders [28, 56, 57]

Rating Code	Bushings	Oil leaks	Oil level	Infra-red	Cooling	Main tank	Oil tank	Foundation	Grounding	Gaskets	Connectors
A	0	0-2	0	0	0-3	0	0	0	0	0	0
B	1-2	3-4	1-2	1	4-6	1-2	1-2	1-2	1-2	1-2	1-2
C	3-4	5-6	3-4	2-3	7-10	3-4	3-4	3-4	3	3-4	3
D	5-7	7-8	5-6	4-5	11-15	5	5-6	5	4-6	5-6	4
E	>7	>8	>6	>5	>15	>5	>6	>5	>6	>6	>4

In addition to the work orders (WO) number in the different transformer components, another score is used to detect negative trends indicating the need for an asset to be subject to maintenance. From the increase of corrective actions during the last 5 years, a classification condition called *General Condition* is created. This classification is in table 4.9 and uses an OR logic between criteria.

Table 4.9: Overall condition based on the trend in corrective maintenance Work Orders [28]

Rating Code	Criterion 1	Criterion 2
A	<3 WOs last 2 years	<10% increase last 5 years
B	>3 WOs last 2 years AND >10% increase last 5 years	>5 WOs last 2 years
C	>5 WOs last 2 years AND >30% increase last 5 years	>10 WOs last 2 years
D	>10 WOs last 2 years AND >50% increase last 5 years	>15 WOs last 2 years
E	>15 WOs last 2 years AND >80% increase last 5 years	>20 WOs last 2 years

4.2.4 Output data

The procedure uses table A.2 to determine the weights of the different condition classifications [56, 57]. For the calculation to begin, letters from A to E are replaced by numbers between 4 and

0, respectively. Equation 4.5 has two parts corresponding to the condition of the transformer and the condition of the tap changer. The second part reflects the ratio of tap changer failures to other faults and were based on [72]. Percentages may vary depending on the fault distribution of the transformer involved.

Table 4.10 provides a description of the general conditions based on the HI result. A schematic of the calculation algorithm is shown in figure A.8.

$$HI = XX\% \times \frac{\sum_{j=1}^{17} K_j.HIF_j}{\sum_{j=1}^{17} 4K_j} + YY\% \times \frac{\sum_{j=18}^{20} K_j.HIF_j}{\sum_{j=18}^{20} 4K_j} \tag{4.5}$$

Table 4.10: Health index scoring for the Kinectrics model [56, 57]

HI	Condition	Description	Approximate Expected Lifetime
85-100	Very Good	Some aging or minor deterioration of a limited number of components	More than 15 years
70-85	Good	Significant deterioration of some components	More than 10 years
50-70	Fair	Widespread significant deterioration or serious deterioration of specific components	Up to 10 years
30-50	Poor	Widespread serious deterioration	Less than 3 years
0-30	Very Poor	Extensive serious deterioration	At end of life

4.3 Methodology based on multi-feature factor

4.3.1 Description

This methodology [73] aims to conduct a comprehensive evaluation of the condition of the power transformer. The health index is an empirical formulation of the transformer health index change over time and is based on the ageing mechanism of the equipment. This HI consists of four sub-indexes that when combined with their respective weights provide a result.

4.3.2 Input data

The health index proposed in [73] consists of four parts: the main health index, the insulating paper health index, the index based on the gas dissolved in the oil and the index for oil quality factor.

4.3.2.1 Main HI

This index is concerned with the age and loading of the transformer and is given by:

$$HI_m = HI_0 \times e^{B\times(T_2 - T_1)} \tag{4.6}$$

- HI is the wanted index
- HI_0 indicates the state in which the transformer starts its operation. The value used is 0.5
- When a transformer reaches the end of its life, its value is close to 6.5. Along with the expected lifetime value, t_{exp}, B (ageing coefficient) can be calculated from:

$$B = f_L \times \frac{ln(6.5/0.5)}{t_{exp}} \tag{4.7}$$

- f_L is the load factor (A.3)
- T_1 is the year corresponding to HI_0, and usually is the year in which the transformer was put into operation
- T_2 is the year that the transformer status is studied, and it can be the present year or some year in the future

4.3.2.2 Insulating paper HI

The insulation paper HI (HI_{iso}) considers essentially the characteristic parameters of the general ageing of the insulation: carbon oxides and furfural content. This index quantifies the general state of transformer ageing. It consists of two parts:

- $HI_{C,O}$: formed by carbon-oxygen content
- HI_{fur} index formed by the furfural content

In order to quantify the ageing level of the transformer insulation, the CO and CO_2 contents and the sum of the contents of the two gases are considered. The three levels are quantified through linear functions as shown in A.4.

The $HI_{C,O}$ index consists of three $F_{C,O}(i)$ parameters with different weights. In [73] all factors are equally important, so all weights are defined as 1/3.

The $HI_{C,O}$ index is calculated as follows:

$$HI_{C,O} = \sum_{i=1}^{3} \omega_i \times F_{C,O}(i) \tag{4.8}$$

The content of furfural corresponds to HI_{fur}. HI_{fur} is given by:

$$HI_{fur} = 3.344 \times (C_{fur})^{0.413} \tag{4.9}$$

The insulating paper HI (HI_{iso}) can be obtained by adding $HI_{C,O}$ and HI_{fur} with their respective weights:

$$HI_{iso} = \omega_1 HI_{C,O} + \omega_2 HI_{fur} \tag{4.10}$$

ω_1 and ω_2 are weights. Since the $HI_{C,O}$ component may come from the decomposition of the oil, whereas the furfural component only comes from the decomposition of the paper insulation, a weight of 0.3 to $HI_{C,O}$ and 0.7 to HI_{fur} was used [73].

4.3.2.3 Index based on DGA

In this sub-index 5 gases ($H_2, CH_4, C_2H_6, C_2H_4, C_2H_2$) are used. The content of these gases enables transformer assessment. In order to quantify the degree of ageing of the transformer insulation. $F_{C,H}(i) = ax(i) + b$ is a linear function where (i) refers to the different types of gases, as can be seen in table A.5.

The HI based on the gases dissolved in the oil can be obtained by:

$$HI_{C,H} = \sum_{i=1}^{5} \omega_i \times F_{C,H}(i) \tag{4.11}$$

In equation 4.11, ω_i corresponds to the weight of each gas. Table 4.11 shows the weight of each of them in the final calculation.

Table 4.11: Weight of each gas [73]

Gas	Weight
H_2	0.2310
CH_4	0.2306
C_2H_6	0.0772
C_2H_4	0.2301
C_2H_2	0.2312

4.3.2.4 Index based on oil quality factor

With the operation of the transformer, the physical and chemical properties of the insulating oil undergo variations.

Performance parameters such as acidity, breakdown voltage, moisture and dielectric loss are used to quantify the index based on the oil quality factor and reflect the condition of the transformer.

These values are defined by linear oil F_{oil}(i) functions and are shown in table A.6. The final oil health index is the weighted sum of the four factors.

The index based on the oil quality factor is obtained by adding the quality factors together with different weights, as shown in equation 4.12:

$$HI_{oil} = \sum_{i=1}^{4} \omega_i \times F_{oil}(i) \tag{4.12}$$

4.3.3 Output data

Through the combination of the main health index and the indexes based on the insulating paper, DGA and the oil quality factor it is possible to obtain a HI_{com} health index that indicates the condition of the transformer.

$$HI_{com} = f \sum_{i=1}^{4} \omega_i \times HI(i) \tag{4.13}$$

In equation 4.13, ω_i corresponds to the weight of each sub-index. Table 4.12 shows the weight of each of them in the final calculation.

Table 4.12: Weight of the four sub-indexes [73]

Sub-index	w_i
HI_m	0.5695
HI_{iso}	0.2661
$HI_{C,H}$	0.0946
HI_{oil}	0.0699

The final health index varies between 0 and 10. Table 4.13 shows the relationship between the index and the condition of the transformer. The lower the value of the index, the better the condition of the transformer.

Table 4.13: Relation between Health Index and Transformer Status [73]

Index value	Health Status	Failure Rate
0-3.5	Slightly aging	Low
3.5-5.5	Obviously ageing, but still belong to normal range	Relatively low, but begin to increase
5.5-7	Ageing beyond the normal range	Significantly increase
7-10	Extremely poor state	Fault may happen at any time

4.4 Methodology for transformer condition assessment

4.4.1 Description

The proposed model [74] allows the evaluation of transformers. The result describes the general health condition of the transformer. In addition, it is a transformer fleet management tool that allows the identification of investment needs.

This model measures the condition of the transformer based on several criteria related to the long-term degradation that result cumulatively at the end of the age of the transformers. This evaluation allows the identification of transformers that are at the end of the life of the operation or close to it.

4.4.2 Input

This HI considers three health sub-indexes corresponding to the quality of the oil:

1. Sub-index based on dielectric strength, dissipation factor, acidity, moisture, colour, and interfacial tension of the oil (Table A.1)

2. Sub-index based on dissolved gas content of the oil (Table 3.3)

3. Sub-index based on furans content of the oil (Table 4.14)

The number of parameters used is expressed by n. The scores of each parameter are indicated by S_i and there are also weighting factors W_i. The weighting factor ranges from 1 to 5, depending on the importance of each parameter.

To find the value of each parameter of HI the following equation can be used (Equation 4.14):

$$HI_{each_parameter} = \frac{\sum_{j=1}^{n} S_i \times W_i}{\sum_{j=1}^{n} W_j} \tag{4.14}$$

The evaluation of each parameter results in a value of A, B, C, D, E and is shown in Table 4.15.

Table 4.14: Furan Scoring [56, 57, 74]

Furaldehyde [ppb]	Rating Code	Condition
0-100	A	Good
100-250	B	Acceptable
250-500	C	Need Caution
5000-1000	D	Poor
$\geq$1000	E	Very Poor

Table 4.15: Assessment of each parameter [74]

Rating Code	Condition	Description
A	Good	<1.2
B	Acceptable	$1.2 \leq 1.5$
C	Need Caution	$1.5 \leq 2$
D	Poor	$2 \leq 3$
E	Very Poor	≥ 3

4.4.3 Output

Table 4.16: HI Score Assessment [74]

No.	Transformer Parameter	K_j	Rating Code	HIF_j
1	DGA	10	A,B,C,D,E	4,3,2,1,0
2	Oil	8	A,B,C,D,E	4,3,2,1,0
3	Furan	5	A,B,C,D,E	4,3,2,1,0

The final calculation of the HI corresponds to the multiplication of the HI factor (HIF_j) with the weight corresponding to each parameter (Equation 4.15). To obtain the HIF_j value it is necessary to convert the rating codes (A to E) into numbers (from 4 to 0). The HIF_j and K_j values of each parameter are shown in Table 4.16.

$$HI_{final} = \frac{\sum_{j=1}^{n} K_j \times HIF_j}{\sum_{j=1}^{n} 4K_j} \times 100\% \tag{4.15}$$

The result will be between 0 and 100. A value of 0 indicates huge degradation in the transformer and the value 100 shows healthy conditions. This is shown as in Table 4.10 which describes the final assessment of the transformer.

4.5 Discussion

In this section it is presented the results of the methodologies selected for the calculation of the HI of the Pracana transformer.

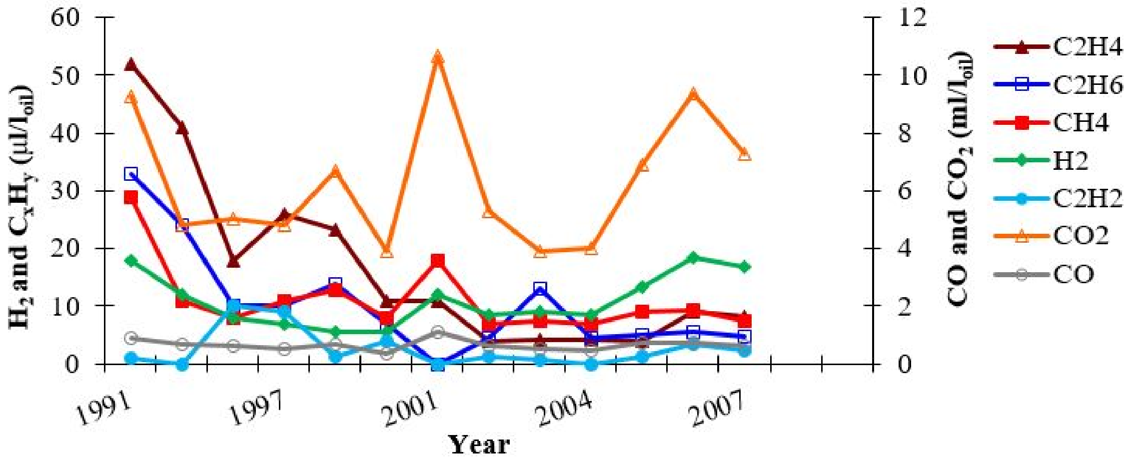

Figure 4.5: Evolution with time in service of insulating oil dis- solved gases by dissolved-gas analysis [20].

4.5.1 Results of the Kinectrics-based model

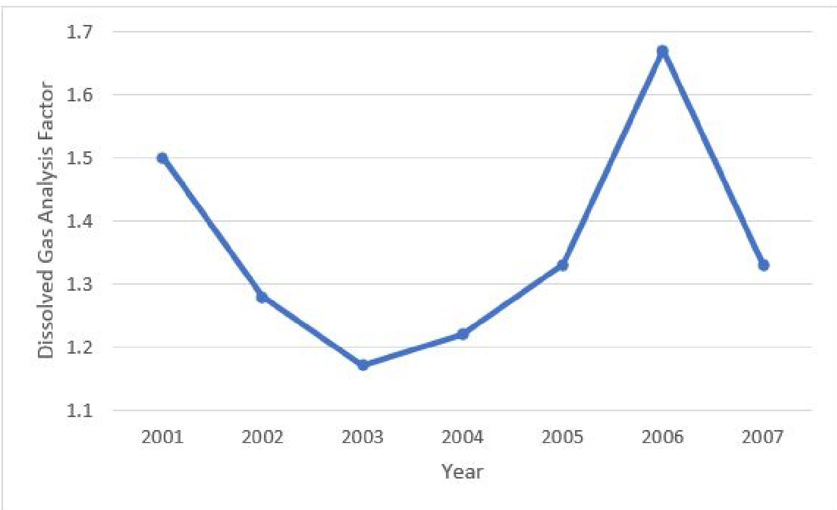

Figure 4.6: Evolution of the Dissolved Gas Analysis Factor over the years.

Through the analysis of figure 4.6, it is possible to verify that the highest calculated values were in the year of 2001 (1.50) and 2006 (1.67). The lowest value was determined in 2003 (1.17).

In relation to 2001, the DGAF value is one of the highest due to the high concentrations of CO and CO_2. When analysing the evolution of these gases over the years, it is verified that their peaks occurred in 2001. Therefore, it is expected that these high concentrations will influence the final result. The high content of these two gases may have led to the degradation of the solid insulation.

In 2003, the overall minimum of this interval was reached. This decrease is due to the decrease of the concentrations of the gases that had influenced the DGAF in the previous year. In addition, the value of 1.17 allows the assignment of rating "A", a situation that will not occur in any other year. From 2003 to 2006, there was a gradual increase in the DGAF.

In 2006, the highest value of the interval is reached. This is due to the increase in C_2H_2 concentration from 1.3 ppm to 3.3 ppm. This increase of 2 ppm led to a change in his score. The increase in score coupled with the fact that this gas has a high weight in the final calculation were the reasons that led to the higher value of DGAF verified. In addition, coupled with this change in C_2H_2 score, CO_2 and CO also have some preponderance, especially carbon dioxide that peaks in that year.

In 2007, the DGAF drops again as the concentration of C_2H_2 returns to a score of 1 and the CO concentration is also lowered, passing the score from "3" to "2".

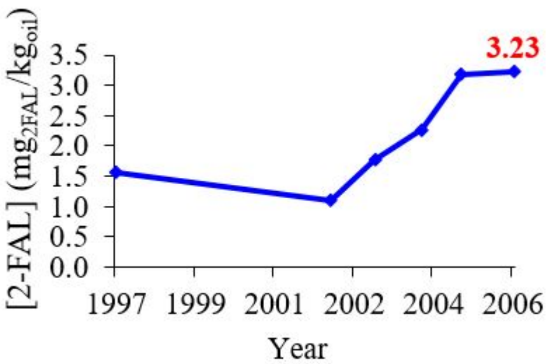

Figure 4.7: Evolution with time in service of insulating oil 2-FAL content by high-performance liquid chromatography analysis [20].

In relation to 2-FAL, its concentration increases from 2002 (1.1 mg_{2FAL}/kg_{oil}) gradually until reaching the maximum value (3.23 mg_{2FAL}/kg_{oil}) when the transformer is put out of service. As mentioned in section 3.1.2 the concentration of 2-FAL is related to the degradation of the paper.

This significant increase in the last 5 years shows that the solid insulation is in a state of advanced degradation. Thus, a low score was assigned to this parameter in order to penalise high values of 2-FAL.

Given that no information was obtained regarding Power Factor over the study time interval, it was assumed that this would be 1. Thus, the rating code assigned to this parameter was "D".

In relation to Load Factor, the power factor of 1 was assumed in the analysis of monthly load peaks. Table 4.17 shows the results of this analysis since 2001:

Table 4.17: Number of instances related with the ratio S_i/S_B

	Number of instances
N0	29
N1	49
N2	5
N3	1
N4	0

From the analysis of table 4.17 it is possible to verify that the transformer had:

- 35% of number of instances between 0 and 0.6
- 58% of number of instances between 0.6 and 1
- 6% of number of instances between 1 and 1.3
- 1% of number of instances between 1.3 and 1.5

Table 4.18: Final value for the load factor

LF
3.26

These results indicate that the transformer has never been subjected to a high number overloads over the analysed time. Thus, in terms of the Load Factor rating, its rating code is "B". By doing an analysis of table 4.18 its value is close to 3.5. If this situation was verified the rating score would be increased to "A".

An attempt was made to increase the rating code by assuming that there would be no load peaks above 1 and those peaks were between 0.6 and 1. The LF value increased to 3.3. If these peaks were between 0 and 0.6, the LF would have a higher value when compared to the remaining ones (3.42), but it would not be possible in any of the attempts to reach the maximum rating code.

Table 4.19: Results from oil analysis of the Pracana transformer

	2007	2006	2005	2004	2003	2002	2001
Breakdown Voltage	70.8	78.2	88.5	77.9	60.1	80.2	55.9
Water content	23.6	22.6	13.3	20.2	13.3	20.1	16.4
Acidity	0.335	0.368	0.304	–	0.280	0.289	0.236
Color	5	5	5.5	5	5.5	5.5	5.5
Interfacial tension	15.6	15.6	–	15.7	17.3	19.4	–

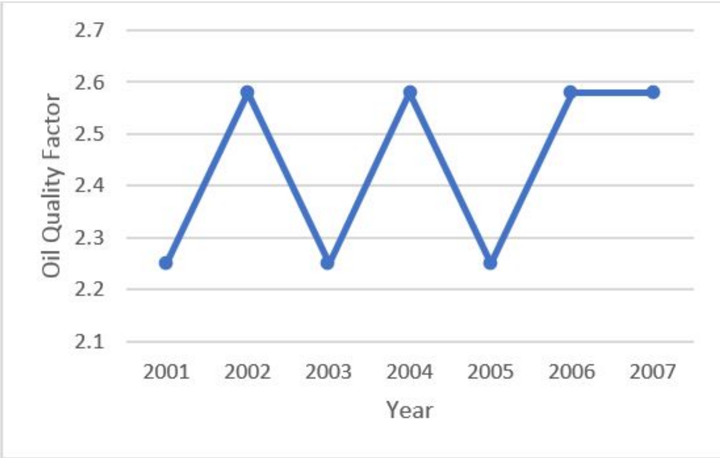

Figure 4.8: Evolution of the Oil Quality Factor over the years

As regards the OQF, it can be observed that the lowest results are found in the years 2001, 2003 and 2005 (2.25). This is due to the fact that moisture has its lowest values in those years allowing a score with less penalty.

The increase in OQF (2001-2002, 2003-2004 and 2005-2006) to its maximum value (2.58) is due only to moisture which has an increase in its score from "1" to "2". The drop (2002-2003 and 2004-2005) is also due to the fact that the moisture score has changed.

The factor that has the most influence and produces more variations in OQF is moisture. All other factors do not influence the final result. Although they vary over the years, their variation "falls" always within the same scoring range.

The results of the methodology are presented below. As in the section that introduces the methodology, it was necessary to convert the rating code to a value from 0 to 4.

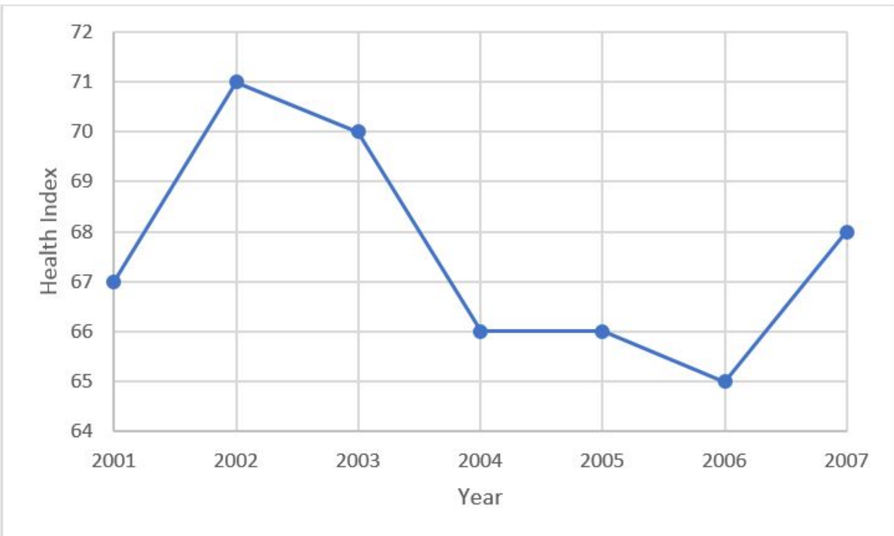

Figure 4.9: Health index final score over the years

The HI value of the Pracana transformer undergoes some variations over the years. The maximum value is reached in the year 2002 (71) and the minimum value occurs in 2006 (65). In 2002 and 2003, according to Table 4.10, the transformer is in a "Good" condition. Although in 2003 the transformer is in this condition, its HI is on the threshold between "Good" and "Fair".

The reason why the HI of the transformer in 2002 has the maximum value is due to the parameter "Overall Condition" that has a better score when compared to 2003. In 2003, the transformer obtained a better score at the DGAF level, but was submitted to a high number of work orders in that year which led to the HI penalty this year.

The variation of HI is, in this case, mainly to three parameters: DGAF, maintenance and Overall Condition. However, the factor that produces the most variations is the DGAF, due to its weight in the overall HI calculation. The year 2003 corresponds to the year in which the DGAF has the best score and the year 2006 with the worst score.

4.5.2 Results for Methodology 2

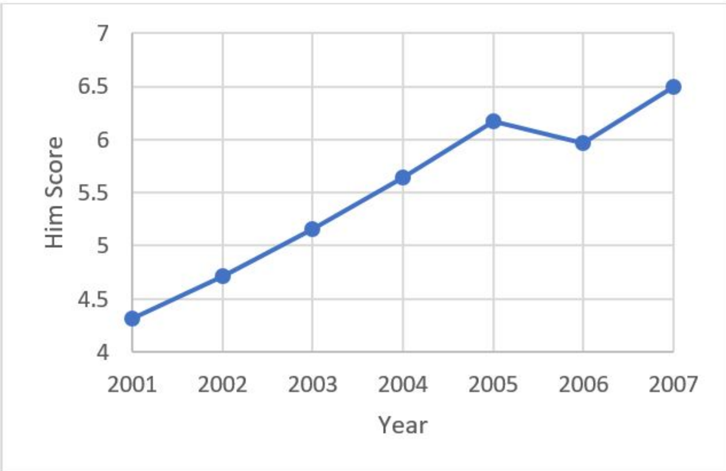

Figure 4.10: HI_{im} index values over the years

Figure 4.10 shows the evolution of the sub-index with more weight in this methodology. In order to know the value of the load factor, an average of the peak load values of each year was calculated.

The value of this sub-index increases from 2001 to 2005 with a decrease in 2006 and again an increase in 2007 (6.5). This fall from 2005 to 2006 is due to the change in the load factor from 1.05 to 1. The increase from 2006 to 2007 is due to the fact that a year has passed.

Figure 4.11 shows the variation of CO and CO_2 and 2-FAL. The minimum value is in 2002 (3.44) and the maximum value in 2006 (5.21).

The drop from 2001 to 2002 is due to the decrease in 2-FAL and the concentrations of the two gases which in 2001 had their maximum concentrations. In 2002, the minimum value is reached since the concentration of 2-FAL is minimal in that year.

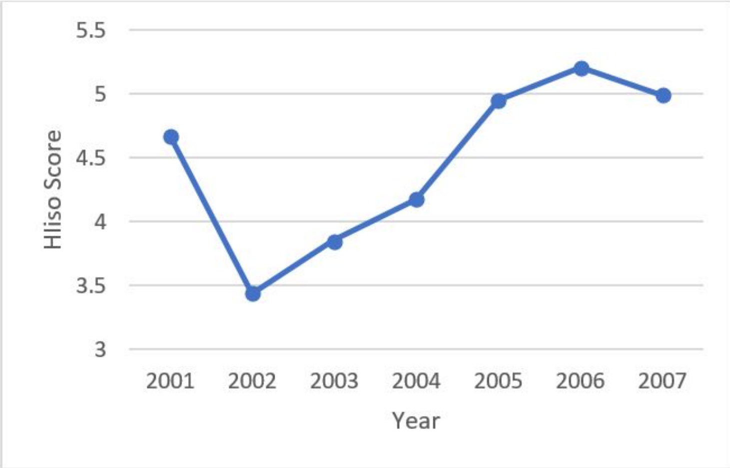

Figure 4.11: HI_{iso} index values over the years.

From 2002 to 2006 there was an increase in the values of this sub-index. This is due to the continuous increase in the concentration of 2-FAL, which has the highest weight in this sub-index, as well as the concentrations of the other gases.

In 2007, although the score decreased in relation to 2006 (difference of 0.2), the concentration of 2-FAL increased in that year. This decrease is due to the decrease in the concentration of CO and CO_2.

The results of this sub-index show the influence of the variation of 2-FAL in relation to the CO and CO_2.

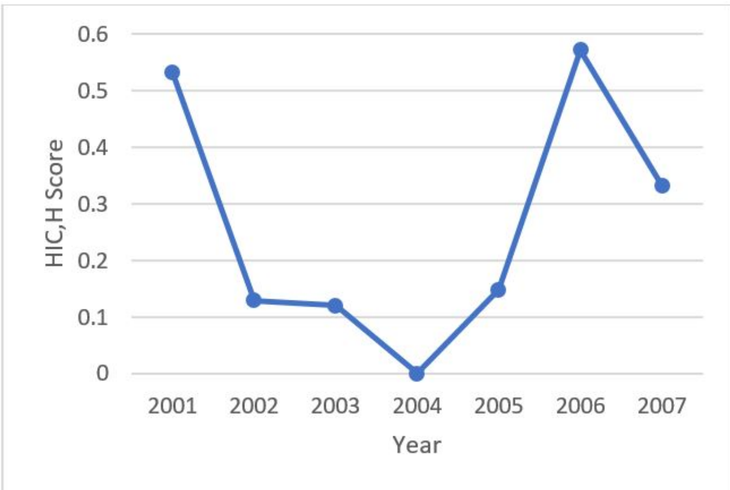

Figure 4.12: $HI_{C,H}$ index values over the years.

Figure 4.12 shows the variation of a set of gases over the years. The minimum value is in 2004 (0) and the maximum in 2006 (0.57).

In the calculation of this sub-index it is verified that although there are variations in the final score only a set of gases influence this score. For example, the concentration of H_2 although it varies over the years, its concentration never exceeds the amount necessary for it to begin to produce changes. The same is true for CH_4 and C_2H_4 which only contribute to the final result in 2001 and C_2H_6 in 2006 and 2003.

The gas that has more weight and produces more variations is C_2H_2 that only has score of zero in 2004 and 2001. Thus, the value of 2004 in which the result is 0 is explained. None of the gases managed to reach the next interval so that the final value would be different from 0.

In relation to the highest values (2001 and 2006), it is due to the high concentration of CH_4 and in 2006 to the combination of the gases C_2H_2 and C_2H_6.

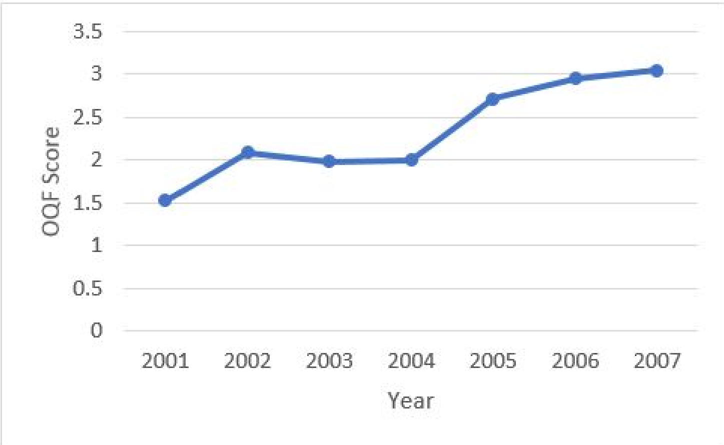

Figure 4.13: Oil Quality Factor values over the years.

The OQF sub-index varies essentially due to moisture and acidity (Figure 4.13). Both moisture and acidity increase over the years. The breakdown voltage does not influence the final result and the interfacial tension produces variations, but as its weight is reduced its influence is small when compared to the humidity and acidity.

The HI value of the Pracana transformer has undergone some variations over the years (Figure 4.14). The maximum value is reached in the year 2007 (5.3) and the minimum value occurs in 2002 (3.75).

The fall from 2001 to 2002 is due to the decrease in the values of the sub-indexes related to DGA and 2-FAL.

The gradual increase over the years is mainly due to the sub-index related to the load factor that increases every year except in 2006. This increase culminates in 2007 in that HI_{oil}, Him reach the maximum values and $HI_{C,H}$ is The second largest of the range.

According to Table 4.13, the transformer is always in a Health Status "Obviously ageing, but still belong to normal range". Although in 2007 the transformer is in this status, its HI is on the threshold of "Obviously ageing, but still belong to normal range" and "Ageing beyond the normal range".

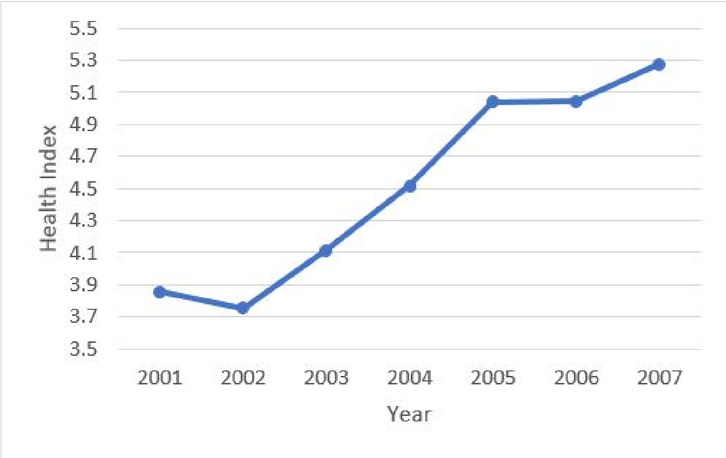

Figure 4.14: HI_{com} index values over the years.

4.5.3 Results for Methodology 3

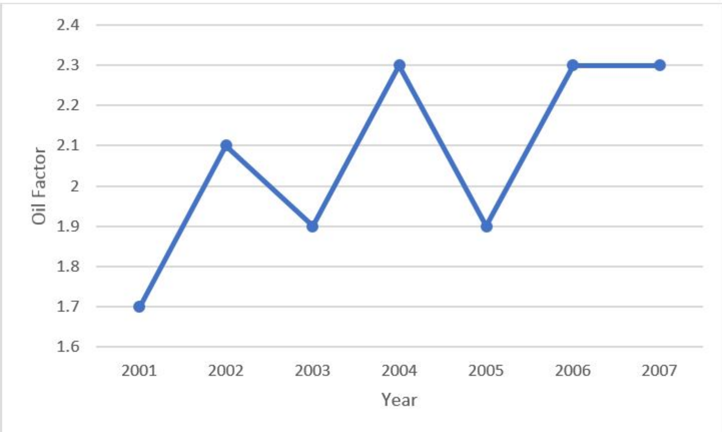

Figure 4.15: Oil Quality Factor over the years.

Regarding the OQF, it can be observed that the lowest result is in 2001 (1.7). This is due to the fact that the value of moisture has low concentration which leads to a corresponding score. Adding to this, the interfacial tension score also leads to the OQF being the at the minimum value.

The increase of the OQF from 2001 to 2002 is due to the fact that the value of moisture (20.1) enters a new range and it is necessary to change its score to the corresponding value. It penalises the increase of its concentration.

The drop in value from 2.1 to 1.9 from 2002 to 2003 is again related to moisture. The interfacial tension also undergoes changes in its score. These variations are not enough to produce changes in the final rating given that its weight does not have as much impact as the moisture does.

The increase observed from 2003 to 2004 is due to the increase in moisture concentration which results in a penalisation of its score.

In 2006, the value of this parameter stabilises at 2.58. It is the maximum verified in this time interval. This stabilisation results from the fact that the moisture score does not change from that year.

Thus, the factor that has the most influence and produces more variations in the calculation of this parameter is moisture.

Acidity and breakdown voltage are factors that do not influence the final result. Although they vary over the years, their variation "falls" always within the same score range. In the case of interfacial tension, its variation despite producing changes in the final result, the rating is always the same (eg: in 2001 and 2003 the final rating is the same: "2").

Regarding DGA, this methodology uses the same key gases and the same scoring criteria as section 4.2. The same situation occurs with respect to 2-FAL.

The HI value of the transformer undergoes some variations over the years. The maximum value that is reached occurs in the year 2003 (0.61) and the minimum value occurs in 2006 (0.30).

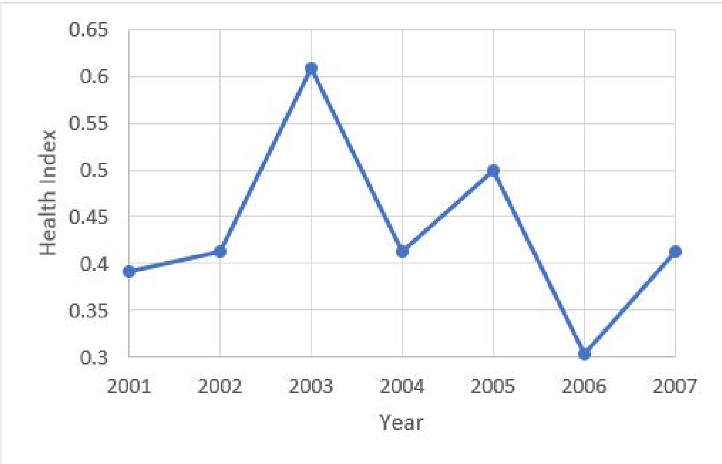

Figure 4.16: Health index final score over the years.

The increase in the HI from 2002-2003 is due to the improvement in the score of the DGA result that goes from 1.5 to 1.17 which allows a change of its rating from "3" to "4". This increase is significant because it allows the transformer to pass from "Poor" to "Fair". However, this value drops in the following year because the DGA and OQF scores increase, causing the transformer to return to a "Poor" condition.

In 2003 and 2005, according to Table 4.13, the transformer is in a "Fair" condition. This was the only years in which such situation occurred. The remaining years are considered to have a "Poor" condition.

In 2005 the HI goes up again, because both the DGA and OQF scores decrease. From 2005 to 2006 the HI decreases continuously, because the value of the parameters is maximum in that year causing its rating to be decreased. HI is at its minimum overall value and the condition of the transformer is at the threshold (0.3) between "Poor" and "Very Poor".

In 2007 the HI increases, due to the decrease of the concentrations of C_2H_2 and CO. OQF does not produce variations in this HI in 2007, since its value is equal to 2006.

4.5.4 Remarks

Through the analysis of the final results it is possible to verify that in terms of better and worse performances the results do not differ much. 2002 is the year in which the transformer HI scores better on two out of three methods (4.2 and 4.3). 2006 is the year in which the transformer health index has the worst score in two out of three methods (4.2 and 4.4).

The methodologies presented generally use the same physical and dielectric properties of oil as they are the most common variables monitored by asset managers. They include acid content and moisture of the oil, breakdown voltage, dissolved gas content of the oil, concentration of 2-FAL.

From the analysis of the results, a set of indicators that influence transversely the condition of the transformer are identified. Moisture, acidity, CO_2, CO, C_2H_2 were indicators that affected the overall condition of the transformer, in this particular case.

However, the 4.4 methodology does not take into account the time for which a transformer has been in service and the extent to which it has been loaded. These two factors may be important in how the HI will reflect the expected deterioration in the condition of the transformer insulation with time in service.

The 4.4 index is then dependent on the analysed oil samples being uncontaminated. However, even if this condition is ensured, it is unlikely that this methodology will perform better than other methodologies. Thus, this methodology may be a starting point for the evaluation of the condition of the transformer provided that other parameters are subsequently evaluated or that a comparative analysis with other methodologies is made.

Comparing the 4.3 and 4.2 methodology, 4.2 is probably a more reliable indicator of the presence of a significant change in the overall health of the transformer. This is due to the fact that it also takes into account other parameters such as maintenance and overall condition.

Nevertheless, it is necessary to emphasise that, for example, the parameter "maintenance" depends on the subjective judgement of a technician who is carrying out the evaluation. Thus, sometimes the criteria used to evaluate these factors are vaguely explained by the authors. This may result in different HIs for the same transformer, depending on the technician who performed the evaluation.

In summary, 4.2 would be most advised to evaluate the condition of the transformer, followed by 4.3 and then 4.4. However, it will be necessary to analyse a larger sample of transformers.

It is necessary to take into account that none of these indicators takes into account the temperature. The increase in temperature favours the degradation of paper insulation. Since the life of a transformer is mainly determined by the condition of its paper insulation, it would be interesting to predict the possible location and temperature of the hot spot affecting the solid insulation, as it will be at this point where there is a greater degradation and where is the answer to what will be the remaining life of the asset.

Chapter 5

Conclusions and Future Work

5.1 Conclusions

Maximising the return on investment of the assets, while at the same time these are operated in a safe and environmentally responsible, has become a business concern.

The fact that power transformers are expensive assets means there is a need to balance investment, maintenance costs and operational performance. It is in this balance that the use of health indexes has become a common method for conducting condition assessments in physical assets (either individually or in large groups).

Pracana's transformer despite still having satisfactory health indexes masked a critical condition that would not allow him to be in operation much longer.

It is not possible to say with 100% certainty how many years of operation this one still had, since there are many variables and conditions in play. However, it is possible to state that its solid insulation was about to reach the 50% threshold with respect to its tensile strength vs. its DP which is considered to be an end-of-life criterion.

Thus, the HI value should be considered with caution, since masking certain problems is evident in this case. The problems are due to the weight assigned to the data involved, but also to the fact that certain data are not considered in the calculation of the algorithm or are subjective. Thus, HI should only answer questions such as: "Which transformers of the fleet need maintenance?" and not to questions such as "What is the remaining lifetime of the transformer?"

Associated with this topic is condition monitoring. Transformer monitoring will bring an increase in costs that did not exist before. This new reality is due to the fact that this type of systems introduces installation, operational and maintenance costs. In addition to these issues, it is necessary to take into account that the inclusion of a monitoring system will not prevent the occurrence of failures.

This statement brings to the fore questions such as: "Will users of this type of monitoring be able to detect transformer failure in a timely manner and prevent it from failing?" The reality is that some users are facing challenges such as accuracy and reliability and sometimes it is difficult to distinguish a false alarm from a real alarm.

Thus, monitoring for optimisation of costs should be directly associated with criticality and fault severity. For example, for transformers that are not considered critical only minimal monitoring would be required (only offline tests would be done). As the criticality hierarchy progresses, offline testing would increase in frequency and would be combined with online monitoring of critical parameters. If higher criticality levels were reached, continuous online monitoring would be performed. This process is applicable to the monitoring of the DGA, bushings, ie any parameter of the transformer.

Another relevant question is: "Which sensors should I install on an old transformer and on a new transformer?". In the case of a transformer already in operation, the minimum monitoring would go through the monitoring of key gases like H_2, CO_2, CO, moisture, acidity, thermal models, OLTC operation model and bushings monitoring. In the case of a new transformer in addition to the parameters mentioned above it could be included the UHF PD monitoring.

If the monitoring of an old transformer was more comprehensive and not minimal, it would go through the following parameters: multigas DGA, moisture, acidity, thermal models, bushings monitoring, OLTC operation model, gas accumulation rate, load current and voltages, fan motors and pump motor currents. In the case of a new transformer it would be included the UHF PD Monitoring.

For the monitoring system of a new transformer a one vendor/solution approach should be used. The solution should be modular and upgradable, ie easy to add new monitoring components with minimal interruption in asset operation. It should still support self-learning algorithms on data collected from sites.

It is necessary to point out that the parameters that are monitored can vary from user to user (hence the existence of several solutions in the market), due to their understanding of how the asset management should be done as well as its financial capacity.

The author would like to highlight parameters such as moisture, acidity, thermal models and DGA. The fact that paper is such an important part in the transformer causes parameters such as moisture, acidity, temperature and dissolved gases to be monitored.

In relation to moisture, acidity and thermal models, these are parameters that can be used in a connected way to infer the state of degradation of the paper. Since taking paper samples is impractical, monitoring these parameters may allow the inevitable degradation of the paper to be delayed.

With regard to dissolved gases, it should be noted that an increase in the concentration of a gas from one year to another may not mean a possible failure. The rate of increase of gas as well as the combination of gases are the factors to take into account. If, for example, H_2 has increased its concentration by 30% over 3 consecutive years, a partial discharge may have occurred.

In short, although the assessment of transformers and their management has always been done, new methods and solutions arise to optimise and increase the longevity of them. The application of health index methods to this management has become a common practice, although there is still no consensus, in other words, there is no standardisation for this subject. The reason may be due to the fact that the degree of importance of the components of the transformers varies from user to user, which makes it difficult to standardise this subject.

5.2 Future Work

The application of the methodologies used in this work to a larger group of transformers would allow the validation or not of the conclusions presented in this work.

A risk and financial analysis would be to interesting to understand if the maintenance in a given transformer was preferable to an investment in a new transformer knowing the possibility of existing fault.

The creation of an algorithm based on neural networks or fuzzy logic, in a predictive maintenance perspective.

Appendix A

Appendix

A.1 Corrective maintenance – examples

40 MVA Transformer 132 / 21.5 kV

Field tests (LV tests):

- Measurement of the transformation ratio, with defect detected in phase U
- Measurement of windings insulation resistance, with 5 kV: OK
- Measurement of capacity and tg δ of the windings, with 10 kV: OK
- Winding resistance measurement, with slight difference in U-phase HV winding
- Physico-chemical analysis and measurement of dissolved gases in oil: Symptom of high energy internal discharge

Diagnosis: Short circuit in the HV (132 KV) winding of the U phase

Figure A.1: Short circuit in the HV (132 KV) winding of the U phase

10 MVA Transformer 60 / 6 kV

The transformer was transported to the factory with symptoms of failure on the OLTC.
LV tests of the active part:

- Measurement of Transformation Ratio: OK

- Measurement of windings insulation resistance, with 5 kV: OK
- Measurement of excitation current with 220V: OK
- Winding Resistance Measurement: OK

Diagnosis: Discharging of the OLTC, caused by poor preventive maintenance and due to surges derived from atmospheric discharges.

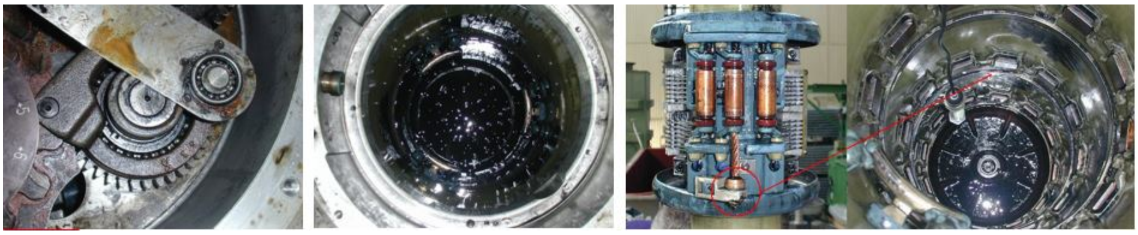

Figure A.2: Ruptor without maintenance: very degraded oil (left and middle figure); Electrical arc between main contact and current disk, phases V and W (right figure)

Proposed repair: Replacing the winding with RC insertion in the middle of the HV winding, or installation of on-line breaker oil treatment filter recommended by the RC manufacturer for these design solutions.

62 MVA Transformer 240 / 10 kV

During preventive maintenance action, symptoms of internal heating were verified by DGA and electrical test results.

Results of LV tests:

- Measurement of Transformation Ratio: OK
- Measurement of insulation resistance of windings, with 5 KV: OK Measurement of capacities, tg δ and excitation current with 10 KV: OK
- Measurement of winding resistance: deviations from the values of origin in particular in phase C of the LV winding.

Diagnosis: Heating located on the inner LV connections to bushings.

Figure A.3: Abnormal heating on the connections of the LV windings to the bushings

90 MVA transformer, 10 / 230 kV

During tests, a high tg δ value was detected at the C1 outlet of the bushings. Due to lack of reserve and due to the need of exploration, the customer did not replace bushings. One of them exploded and burned; Due to the efficiency of the fire protection system, it was restricted to the bushing.

Actions taken:

- Diagnostic tests
- Internal inspection
- Replacement of bushings
- Refurbishment of the power transformer (cleaning, painting, replacement of accessories)

Diagnosis: Fire was restricted to the bushing. Tests do not show problems in the active part. The transformer can be recovered and replaced in service after the replacement of the bushings and reconditioning.

Figure A.4: 220 kV bushing destroyed by fire

40 MVA transformer, 60/6 kV

During preventive maintenance action, internal heat symptoms were detected by DGA.

Results of LV tests:

- Measuring Transformation Ratio: OK
- Measurement of insulation resistance of windings, with 5 kV: OK
- Capacitance measurement, tg δ and excitation current at 10 kV: OK
- Winding Resistance Measurement: OK

Diagnosis: Heating located on a crimping of an internal LV connection.

Figure A.5: Crimping of an internal LV connection

A.2 Faults in OLTCs – examples

Example 1

- Fissures in the bakelite tub
- Deformations in the bakelite tub
- Selector attachment detachment

Figure A.6: Faults in OLTCs – example 1

Example 2

- Selector detachment from the rupture tank, caused the OLTC destruction

Figure A.7: Faults in OLTCs – example 2

A.3 Scoring Tables for Kinectrics Health Index Model

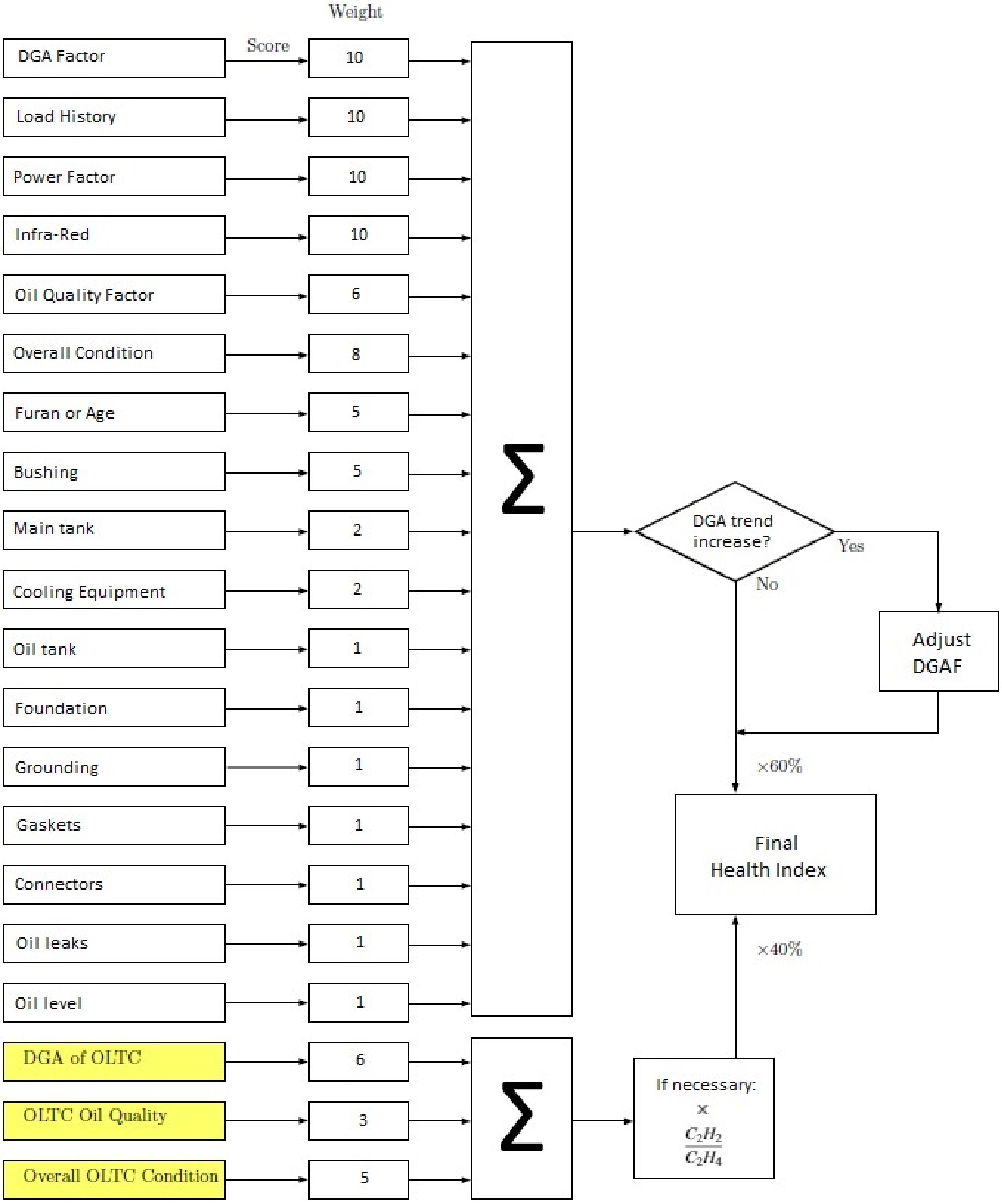

Figure A.8: Schematic of the Kinectrics health index module [28]

Table A.1: Grading method for Oil test parameters [56, 57]

	U $\leq$ 69kV	69kV <U <230 kV	230 kV $\leq$ U	Score (S_i)	Weight (W_i)
Dielectric Strength [kV]	$\geq$ 45	$\geq$ 52	$\geq$ 60	1	3
	35-45	47-52	50-60	2	
	30-35	35-47	40-50	3	
	$\leq$ 30	$\leq$ 35	$\leq$ 40	4	
Interfacial tension [dyne/cm]	$\geq$ 25	$\geq$ 30	$\geq$ 32	1	2
	20-25	23-30	25-32	2	
	15-20	18-23	20-25	3	
	$\leq$ 15	$\leq$ 18	$\leq$ 20	4	
Acid number [mg KOH/g oil]	$\leq$ 0.05	$\leq$ 0.04	$\leq$ 0.03	1	1
	.05-0.1	0.04-1.0	0.03-.07	2	
	0.1-0.2	1.0-0.15	0.07-0.10	3	
	$\geq$ 0.2	$\geq$ 0.15	$\geq$ 0.1	4	
Water content [ppm]	$\leq$ 30	$\leq$ 20	$\leq$ 15	1	1
	30-35	20-25	15-20	2	
	35-40	25-30	20-25	3	
	$\geq$ 40	$\geq$ 30	$\geq$ 25	4	
Color	$\leq$1.5			1	2
	1.5-2.0			2	
	2.0-2.5			3	
	$\geq$2.5			4	
Dissipation factor [%] (at 90°C)	$\leq$0.05			1	3
	0.05-0.1			2	
	0.1-0.5			3	
	$\geq$0.5			4	

Table A.2: Health Index Scoring [56, 57]

#	Transformer Condition Criteria	Weight	Condition Rating	HIF
1	DGA	10	A,B,C,D,E	4,3,2,1,0
2	Load History	10	A,B,C,D,E	4,3,2,1,0
3	Power Factor	10	A,B,C,D,E	4,3,2,1,0
4	Infra-Red	10	A,B,C,D,E	4,3,2,1,0
5	Oil quality	6	A,B,C,D,E	4,3,2,1,0
6	Overall Condition	8	A,B,C,D,E	4,3,2,1,0
7	Furan or Age	5	A,B,C,D,E	4,3,2,1,0
8	Bushing condition	5	A,B,C,D,E	4,3,2,1,0
9	Main Tank Condition	2	A,B,C,D,E	4,3,2,1,0
10	Cooling equipment	2	A,B,C,D,E	4,3,2,1,0
11	Oil Tank Condition	1	A,B,C,D,E	4,3,2,1,0
12	Foundation	1	A,B,C,D,E	4,3,2,1,0
13	Grounding	1	A,B,C,D,E	4,3,2,1,0
14	Gaskets	1	A,B,C,D,E	4,3,2,1,0
15	Connectors	1	A,B,C,D,E	4,3,2,1,0
16	Oil leaks	1	A,B,C,D,E	4,3,2,1,0
17	Oil level	1	A,B,C,D,E	4,3,2,1,0
18	DGA of OLTC	6	A,B,C,D,E	4,3,2,1,0
19	OLTC Oil Quality	3	A,B,C,D,E	4,3,2,1,0
20	Overall OLTC Condition	5	A,B,C,D,E	4,3,2,1,0

A.4 Scoring Tables for methodology 3

Table A.3: Load Factor as a function of percent load for transformer [73]

Load (%)	Load Factor (f_L)
0–40	1
40–60	1.05
60–70	1.1
70–80	1.25
80–150	1.6

Table A.4: Calculation for Carbon-Oxygen Factor F_{C-O} [73]

Factor	X_i (μL/L)	a	b	$F_{C,O}(i)$
CO	0–300	0.0067	0	ax_1+b
	300–900	0.0017	1.5	
	900–1000	0.02	-14.97	
	1000-1400	0.0125	-7.5	
	>1400	—	—	10
CO_2	0–2400	0.0008	0	ax_2+b
	2400–3000	0.0033	-6.0	
	3000–5000	0.0005	2.4	
	5000–10000	0.0008	0.9	
	10000–13000	0.0003	5.9	
	>13000	—	—	10
$CO+CO_2$	0–3000	0.00067	0	ax_3+b
	3000–10000	0.00014	1.59	
	10000–170000	0.000033	2.66	
	170000–350000	9.44×10^{-6}	6.65	
	>350000	—	—	10

Table A.5: Hydrocarbon gases function $F_{C,H}$ [73]

Factor	X_i (μL/L)	a	b	$F_{C,H}(i)$
H_2	≤ 30	0	0	ax_1+b
	30–50	0.1	-3	
	50–100	0.06	1	
	100–500	0.0125	3.75	
	>500	—	—	10
CH_4	≤ 10	0	0	ax_2+b
	10–15	0.4	-2	
	15–125	0.0727	0.9	
	>125	—	—	10
C_2H_6	≤ 5	0	0	ax_3+b
	5–20	0.1333	-0.6667	
	20–35	0.2	-2	
	35–70	0.125	0.625	
	>70	—	—	10
C_2H_4	≤ 10	0	0	ax_4+b
	10–30	0.1	-1	
	30–50	0.15	-2.5	
	50–175	0.04	3	
	>175	—	—	10
C_2H_2	≤ 0.5	0	0	ax_5+b
	0.5–3	0.8	-0.4	
	3–5	1.5	-2.5	
	5–35	0.1667	4.167	
	>35	—	—	10

Table A.6: Linear functions for Oil Quality Factor [73]

Factors	Weight	U $\leq$ 69kV
Micro-Water (mg/L)	0.4565	$F_{oil}(H_2O) = \begin{cases} 0 & x \leq 20 \\ 0.2x-4 & x \in]20,30] \\ 0.4x-10 & x \in]30,45] \\ 10 & x > 45 \end{cases}$
Acid Value (mgKOH/g)	0.2598	$F_{oil}(acid) = \begin{cases} 0 & x \leq 0.015 \\ 23.53x-0.353 & x \in]0.015,0.1] \\ 20x & x \in]0.1,0.2] \\ 40x-4 & x \in]0.2,0.3] \\ 10 & x > 0.3 \end{cases}$
Dielectric Loss (25°C)	0.1386	$F_{oil}(\delta) = \begin{cases} 0 & x \leq 0.05 \\ 20x-1 & x \in]0.05,0.15] \\ 5.714x+1.143 & x \in]0.15,0.5] \\ 4x+2 & x \in]0.5,1.5] \\ 10 & x > 1.5 \end{cases}$
Breakdown Voltage (kV)	0.1452	$F_{oil}(V) = \begin{cases} 10 & x \leq 30 \\ -0.4x+20 & x \in]30,40] \\ -0.667x+30.68 & x \in]40,43] \\ -x+45 & x \in]43,45] \\ 0 & x > 45 \end{cases}$

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